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SPATIOTEMPORAL CHARACTERISTICS OF VISUAL LOCALIZATION— PHASE II

Annual Technical Report
Covering the Period August 1988 Through August 1989

August 1989

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SRI Project 6616

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	Unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S) Annual Report SRI Project 6616	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR·TR· 89-1246

6a. NAME OF PERFORMING ORGANIZATION SRI International	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR\NL
6c. ADDRESS (City, State, and ZIP Code) 333 Ravenswood Avenue Menlo Park, California 94025		7b. ADDRESS (City, State, and ZIP Code) Building 410 Bolling AFB, D.C. 20332

8a. NAME OF FUNDING / SPONSORING ORGANIZATION AFOSR	8b. OFFICE SYMBOL (If applicable) NL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-88-K-0008

8c. ADDRESS (City, State, and ZIP Code) Building 410 Bolling AFB, D.C. 20332-6448	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO. 61102F	PROJECT NO. 2313	TASK NO. A5	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Spatiotemporal Characteristics of Visual Location—Phase II

12. PERSONAL AUTHOR(S)
Christina A. Burbeck, Duane K. Boman, Yen Lee Yap

13a. TYPE OF REPORT Annual	13b. TIME COVERED FROM Aug. 88 TO Aug. 89	14. DATE OF REPORT (Year, Month, Day) 1989 August	15. PAGE COUNT 164

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	human vision, visual psychophysics, visual spatial localization .
6	4		

19. ABSTRACT (Continue on reverse if necessary and identify by block number) were conducted

We have conducted psychophysical experiments to determine (1) the contribution of local spatial filters to separation discrimination and (2) the properties of mechanisms that enter into subsequent stages of spatial processing i.e., separation discriminators. The separation, eccentricity, spatial extent, exposure duration, and proximity of the targets to other objects were manipulated. We found that the extent of the target was more important for discrimination of relatively small (rather than large) separations at any given eccentricity, supporting the idea that an additional stage beyond the local spatial filters is necessary to explain performance of separation discrimination. The proximity of other spatial features was found to affect thresholds only for briefly exposed targets, implying that subsequent mechanisms can select the frequency content of the information carried by the local spatial filters. Separation discrimination appeared to be performed by two different types of separation discriminators: one largely separation-dependent, and the other separation-independent but strongly eccentricity-dependent. Finally, we determined that (unlike the local spatial filters) the separation discriminator processes information serially, with each separation taking at least 100 ms to encode. keywords.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL John F. Tangney	22b. TELEPHONE (Include Area Code) (202) 767-5021	22c. OFFICE SYMBOL NL

DD Form 1473, JUN 86   Previous editions are obsolete

(SRI on-line version)

89 9 27 047

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* Bound separately

I STATEMENT OF WORK
(Unchanged from our original proposal)

We propose to conduct experimental psychophysical research, together with the necessary and appropriate theoretical development, on the three topics listed below:

(1)   Test and explore the theory that spatial-interval discrimination thresholds can be determined at any of several stages of processing, the precise stage depending on the details of the stimulus. Specifically, we will seek those conditions that cannot be accounted for by linear spatial filters.

(2)   Explore the source of the exposure duration effect in localization judgments, by investigating its dependence on both the spatial frequency content and retinal eccentricity of the stimulus, and by relating these results to properties of the spatial filters as revealed in analogous contrast-detection experiments.

(3)   Investigate the spatial characteristics of the receptive fields underlying the proximal localization mechanisms and relate them to those of linear spatial filters.

Research to date on these topics has broadened and deepened the scope of our research, as indicated in the Status of Research (Section II). The goals of our research and the theoretical framework remain essentially unchanged from the original proposal, with the refinement that we are now attempting to model separation discrimination thresholds in terms of just two stages of processing: local spatial filters followed by the separation discriminator. This approach allows us to develop more specific and testable hypotheses as to the nature of the processing involved.

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II STATUS OF RESEARCH

There is now ample evidence, from our results and from results obtained in other labs, that local spatial filters alone cannot account for localization thresholds. The clear establishment of that fact leads to the questions: What are the properties of the separation discriminator, and how does the separation discriminator make use of information from the local spatial filters?

A. COMPLETED STUDIES

During the past year, we have completed several studies on the properties of the separation discriminator (that is, the processing that is specific to the extraction of information about the separation between two objects, or the spatial extent of a single object). For continuity, the sub-section titles used here were taken from the final report for Contract F49620-85-K-0022 whenever possible.

1. Role of Retinal Inhomogeneity in Separation Discrimination Judgments

We investigated the effects of retinal eccentricity on separation discrimination thresholds using targets of variable separation that were presented on an isoeccentric arc, and using targets of constant nominal separation and variable eccentricity. Target length and exposure duration were also manipulated to check the generality of the findings. We found that when retinal eccentricity is held constant, separation discrimination thresholds increase with increasing separation up to a separation roughly equal to the eccentricity, and then become constant. Eccentricity has only a small effect on separation discrimination thresholds when the target size and separation are relatively large. Exposure duration is an important factor only when the separation is small. Line length is an important factor only for very short lengths.

The results of these experiments were reported in the manuscript "Two Mechanisms for Localization? Evidence for Separation-Dependent and Separation-Independent Processing of Position Information," which has been accepted for publication by *Vision Research* . A copy of the manuscript is included as Appendix A.

These experiments led to two new studies:

- A more detailed analysis of the effect of length on separation discrimination thresholds, which is nearly complete.

- An investigation of the relationship between the mechanism underlying performance in the separation-independent region and that which encodes the retinal position of the target.

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Both studies are described below.

2. *Separation Discrimination in the Presence of Flanking Lines*

By flanking the separation discrimination targets with parallel lines, and manipulating the exposure duration and spatial frequency content of the stimulus, we were able to determine that the spatial frequency range that is used by the separation discriminator to represent individual targets varies with context. If the target lines are crowded on both sides by flanking lines, high spatial frequency filters are used; if the target lines are presented with flanking lines on only one side, or with no flanking lines at all, then lower spatial frequency filters carry the target information.

Results of these experiments are reported in the manuscript "Spatial-Filter Selection in Large-Scale Spatial-Interval Discrimination," which has been accepted for publication by *Vision Research*. A copy of the final version is given in Appendix B.

3. *Serial vs. Parallel Processing of Length Information*

At the beginning of this contract year, we anticipated that this study comparing the time-course of separation discrimination and bisection would result in a Research Note to *Vision Research*. Instead, the study proved to be so interesting that it resulted in a fairly lengthy paper, which has recently been submitted to *Vision Research* for the special issue honoring Professor Gerald Westheimer. The submitted manuscript is attached as Appendix C.

Briefly, we found that bisection thresholds are poorer than separation discrimination thresholds at short durations, but are the same or better at long durations. We modeled these data by a sequential processor that analyzes only one separation at a time, requiring twice as long to get the the two pieces of information from a bisection stimulus as it does to get one piece of information from a separation discrimination stimulus. We confirmed this interpretation in several ways, by manipulating stimulus contrast, presence of the mask, and definition of the bisection threshold. (Our standard definition is not the one most widely used in the literature, although it is the one originally used by Volkmann and by Fisher—two pioneers in the field.) Results of all of these manipulations confirm our sequential processing model of bisection. The results also validate our definition of the bisection threshold. Finally, they indicate that the separation discriminator can continue to extract information about a stimulus separation for at least 100 ms after the termination of the stimulus. (We show that this integration cannot be attributed to the properties of the local spatial filters, but is specific to the separation discriminator.)

4. *Rapid Pattern Discrimination*

In this collaborative study with Dr. Ben Kröse, now at University of Amsterdam, we

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looked at the effect of distracter items on reaction times to a target whose location was always known. The SRI eyetracker was used to fix the location of the target in the periphery. This research was reported in the manuscript "Spatial Interactions in Rapid Pattern Discrimination," which is included as Appendix D. This manuscript has been accepted for publication by *Spatial Vision*.

B. RESEARCH IN PROGRESS

Several studies continue to be developed.

1. Methodology of Separation Discrimination

This research was begun during a brief visit by Prof. Dan Swift of the University of Michigan to our laboratories. We began by looking at the effect on separation discrimination thresholds of using a remembered mean as a referent. This study grew to include orientation discrimination, where one would expect there to be natural referents at horizontal and vertical, and perhaps at some other orientations. The results of this preliminary study were reported at the Optical Society of American Annual Meeting in October 1988. We are continuing the effort in collaboration with Dr. Lex Toet at the Institute for Perception TNO, in the Netherlands. (We cannot display the necessary stimuli on our laboratory apparatus, whereas Dr. Toet can.)

2. Pattern Adaptation Effects: Finding the Site of Length Judgments

We continue to investigate the problem of how perceived size or separation is related to the local spatial filters in this study of the effects of pattern adaptation on frequency discrimination thresholds and on perceived spatial frequency. The perceived spatial frequency shift predicts that frequency discrimination thresholds should also be affected by pattern adaptation. We are investigating that relationship. Progress on this study has been slowed by repeated failure to replicate Regan and Beverly's finding that frequency discrimination thresholds are indeed elevated following pattern adaptation. We now have one observer who shows the effect. Data collection, which is extremely time consuming, continues. We believe that the study is worthwhile because it addresses the important question of the relationship between discrimination thresholds and the subjective percept.

C. NEW RESEARCH DIRECTIONS

1. Line-Length Effects in Separation Discrimination

Our study of line-length effects began as a control experiment, but proved to have some very interesting features which we have explored. Dr. Yap is pursuing this investigation and will be submitting a manuscript to *Vision Research* on this topic. A draft manuscript is attached as Appendix E.

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2. *Absolute Retinal Location Judgments*

When the separation is large (more than half the eccentricity), separation discrimination thresholds are independent of the separation. This independence suggests that the limiting factor in the underlying mechanism is the accuracy with which the individual target locations can be encoded. We will be testing this hypothesis. We will use the SRI eyetracker to stabilize the image and measure thresholds for discriminating between retinal positions of a target in the absence of another reference stimulus. The experiments will be performed in the dark with only the target visible. We have had to upgrade and modify the Generation V eyetracker, which was a prototype, to do this experiment. That is now complete and we are about to begin experimentation.

3. *Flanking Lines and Grouping*

We have completed one study on the effects of flanking lines, but many interesting questions remain. The effects of the flanking lines appears to depend on the relationship between distance from the flanking lines to the targets and the separation between the targets. If the flanking-line to target distance is small relative to the separation then separation judgments appear to depend on the position of the target and flanking lines as a group instead of just on the position of the target. Methodological issues are still being worked out on this problem. However, manipulating exposure duration continues to prove to be a useful.approach. We are also uncovering interesting, albeit p. :zling, effects of target type, e.g., black or white bars. This continues to be a subject for exploration.

4. *Research on the Perceptual Effects of a Foveal Scotoma*

This research, which is funded by DARPA through this contract, is reported on in Appendix F (bound separately).

III PUBLICATIONS AND MANUSCRIPTS

Kröse, Ben J.A., and Christina A. Burbeck, "Spatial Interactions in Rapid Pattern Discrimination," *Spatial Vision* (in press).

Burbeck, Christina A. and Yen Lee Yap, "Spatial-Filter Selection in Large-Scale Spatial-Interval Discrimination," *Vision Research* (in press).

Burbeck, Christina A., and Yen Lee Yap, "Two Mechanisms for Localization? Evidence for Separation-Dependent and Separation-Independent Processing of Position Information," *Vision Research* (in press).

Burbeck, Christina A., and Yen Lee Yap, "Spatiotemporal Limitations in Bisection and Separation Discrimination," submitted to *Vision Research*..

Burbeck, Christina A., "Encoding Spatial Relations," working title of chapter being written for *Vision and Visual Dysfunction, Vol. 14, Pattern Recognition by Man and Machine,* Prof. Roger Watt, ed. (to be published by Macmillan Press, London).

Yap, Yen Lee, "The Length Effect in Separation Discrimination," to be submitted to *Vision Research.*

IV PROFESSIONAL PERSONNEL

Christina A. Burbeck, Principal Investigator

Yen Lee Yap, Ph.D., Postdoctoral Fellow, SRI International

Ben J.A. Kröse, Ph.D., University of Amsterdam

Lex Toet, Ph.D., Institute for Sensory Physiology, Soesterberg.

V INTERACTIONS

A. SPOKEN PAPERS:

Burbeck, Christina A., and Dan J. Swift, "The Remembered Referent in Separation Discrimination and Vernier Acuity Tasks," Annual Meeting, Optical Society of America, Santa Clara, California, 31 October - 4 November 1988.

Kelly, D. H., and Christina A. Burbeck, "Enhancement of Contrast Sensitivity by Microsaccades," Annual Meeting, Optical Society of America, Santa Clara, California, 31 October - 4 November 1988.

Yap, Yen Lee, and Christina A. Burbeck, "Two Mechanisms for Large-Scale Localization", Annual Meeting, Optical Society of America, Santa Clara, California, 31 October - 4 November 1988.

Yap, Yen Lee, and Christina A. Burbeck, "Integrating Size Information: Temporal Integration in Bisection and Separation Discrimination" , poster presented at ARVO Annual Meeting, Sarasota, Florida, 30 April - 5 May 1989.

Burbeck, Christina A., and Yen Lee Yap, "Integrating Size Information: Using the Second Spatial Dimension", ARVO Annual Meeting, Sarasota, Florida, 30 April - 5 May 1989.

B. CONSULTATIVE AND ADVISORY FUNCTIONS

Under this contract, we are performing research on the effects of foveal scotomas on performance of a wide range of visual tasks. This research is sponsored by DARPA, and is described in Appendix F, which is bound separately.

Dr. Burbeck will be serving on the NSF Review Panel for the Sensory Systems section, beginning this fall.

Dr. Burbeck served as an ad hoc reviewer for the NIH National Eye Institute, Study Section B in June of 1988. (This was not included in last year's report.)

Appendix A

TWO MECHANISMS FOR LOCALIZATION?
EVIDENCE FOR SEPARATION-DEPENDENT
AND SEPARATION-INDEPENDENT
PROCESSING OF POSITION INFORMATION

Christina A. Burbeck and Yen Lee Yap

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Two Mechanisms for Localization?
Evidence for Separation-Dependent and Separation-Independent
Processing of Position Information

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keywords: separation discrimination, size, eccentricity, periphery, spatial summation, temporal summation, spatial vision

running head: Two Mechanisms for Localization?

Abstract — The Weber function for separation discrimination – i.e., Δs as a function of separation s – is typically measured using a pair of targets presented roughly symmetrically relative to the fovea. With this paradigm, as the separation increases, the eccentricity of the individual targets increases also. To disentangle the effects of separation and eccentricity on the Weber function for separation discrimination, we systematically examined each of these variables and also examined the effects of target size and exposure duration. Separation discrimination thresholds were measured for average separations from 3° to 6° across a wide range of eccentricities, and for eccentricities of 2.5° to 10° for a range of separations. The dependence of threshold on target size was measured by varying the length of the stimuli from 1 to 120 arcmin; the dependence on exposure duration war ͜ ,sured using durations of 100 and 500 ms at 10° eccentricity for comparison with dat ͜ 'ected previously at smaller eccentricities. We found that for separations less than the eccentricit͡y ͜ ͜e targets, thresholds depend primarily on separation; for larger

separations, thresholds depend solely on eccentricity. In general, unless the targets are very small or quite brief, the spatial and temporal characteristics of the targets are not major contributors to the slope of the Weber function. Two mechanisms are proposed to account for thresholds in the two regions, one separation-dependent and one separation-independent.

I Eccentricity Effects for Fixed Separations

Introduction

When measured in the standard way, with fovea-centered stimuli, separation discrimination and bisection thresholds increase almost proportionally with separation; that is, the Weber function for separation – Δs measured as a function of s – is linear on a log scale with a slope of approximately one (Fechner, 1858; Volkman, 1858; Westheimer and McKee, 1977; Andrews and Miller,1978; Levi and Klein, 1983; Klein and Levi, 1985, 1987; Burbeck, 1987; Toet, van Ekhout, Simons and Koenderink, 1987). Although this is one of the fundamental properties of localization thresholds, it remains unexplained. Several local-spatial-filter models of spatial vision have been proposed to account for data obtained at small separations (e.g., Wilson and Gelb, 1984; Klein and Levi, 1985). However, localization thresholds cannot, in general, be accounted for solely by the responses of individual local spatial filters (Morgan and Ward, 1985; Burbeck, 1987, 1988a; Toet et al., 1987). In particular, the Weber function for separation cannot be explained by an increase in spatial uncertainty with decreasing spatial frequency. An alternative explanation must be found. Levi et al. (1988) suggest that localization thresholds increase with increasing separation because the retinal eccentricity of the individual targets increases with increasing separation when measured with fovea-centered stimuli. Supporting this theory are

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experiments they conducted in which bisection thresholds were measured for targets positioned on a chord of an isoeccentric arc, 10° from the fovea. They found little variation in threshold with separation, tor separations ranging from 3.5° to 10°, and concluded that the slope of the Weber function for separation was simply a consequence of retinal inhomogeneity. According to this theory, the decrease in spatial sampling density with increasing eccentricity is the sole determinant of the slope of the Weber function for separation.

If the Weber function for separation is actually independent of separation, then holding the separation constant and varying only the eccentricity should yield the traditional Weber function for separation, with a slope of almost unity. In our first experiment we tested this possibility by measuring separation discrimination thresholds as a function of target eccentricity for a fixed separation. Since contrast sensitivity studies show that the effect of eccentricity depends on the spatial characteristics of the stimulus (e.g. Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978; Rovamo, Virsu, and Nasanen, 1978), we chose large, high-contrast bar targets to try to bypass limitations imposed at distal stages of visual processing.

Methods

The stimuli were all generated on a CRT with a mean luminance of 90 cd/m^2 (Conrac Model 2400, 48.3-cm diagonal, 60-Hz noninterlaced frame rate, 512 x 512 pixels). For the first experiment, each stimulus was a pair of horizontal bars, presented at 90% contrast ((L_{max}-$L_{background}$)/$L_{background}$) with abrupt onset and termination for a duration of 500 ms. The individual bars were nearly square, measuring 1.3° horizontally x 1.1° vertically. The bar pairs were presented with an average vertical separation of 4.2° at a viewing distance of 1 m.

The vertical separation between the targets was varied from trial to trial to determine the separation discrimination threshold. The observer's task was to report whether the separation presented on a given trial was larger or smaller than the average separation that he had seen on

previous trials. Practice trials at the beginning of each data collection session enabled the observer to learn the average separation.

The method of constant stimuli was used with fourteen separations. A run consisted of 154 trials, of which the first 14 were practice and were excluded from threshold calculations. As many as 15 runs were conducted for a given observer and eccentricity to ensure that practice effects did not affect the final results. No practice effects were found for either of our experienced observers in this task. We calculated thresholds at the 84% correct level using a program that optimized the likelihood of the best-fitting cumulative normal function, which is equivalent to standard probit analysis. This program also generated the standard errors, which are shown.

To prevent the observer from using the edges of the display as cues to position, the stimulus was centered horizontally on the display so that it was well away from the edges. We also varied the vertical position of the stimulus on the display randomly from trial to trial within a range of ± 0.7°.

For the non-fovea-centered stimuli, the stimuli were presented to the nasal retina of the right eye. Eccentricity was varied by instructing the observer to fixate a small fixation dot optically superimposed on the display and visible at all times. For the fovea-centered stimuli, no fixation marks were used, and the observer was instructed to fixate the center of the display.

Results

Data, plotted as a function of the eccentricity of the targets, are shown in Fig. 1 for two observers. Between 2° and 10°—15°, eccentricity had little or no effect. However, because the stimulus was displaced vertically by a random amount from trial to trial (up to 0.7° variation in the vertical placement), there could be a small dependence on eccentricity at the smallest eccentricities that was not evident in the data. On the other hand, if eccentricity were solely responsible for the

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slope of the Weber function, then the threshold would have nearly doubled whenever the eccentricity doubled. This clearly did not occur for these stimuli for eccentricities less than 10° or 15°. Beyond 15°, larger eccentricity effects were obtained.

To determine whether the insensitivity to eccentricity at small eccentricities was specific to our choice of stimuli, we repeated the experiment with smaller stimuli and a briefer presentation, using two new separations, 2.9° and 5.9°. The targets were 4 x 30 arcmin, presented for 200 ms. Data for the two observers are shown in Fig. 2. For eccentricities up to 10° to 15°, the effect of eccentricity was similar to that seen with the larger targets, indicating that the small effect of eccentricitiy in this region is not specific to the stimulus used. For separations between 2° and 10°, the effect of eccentricity was never large enough to account for the slope of the fovea-centered Weber function. To account for that slope, the slope of these data would have to be approximately unity. Palmer and Murakami (1987) also reported similarly small eccentricity effects.

At larger eccentricities, thresholds obtained with these smaller, briefer targets increased more steeply with eccentricity than did thresholds for the larger, longer-duration targets. The amount of that increase depended on the separation, the rise for the 2.9° separation being greater than for the 5.9° separation. This rise could not be caused by the limits of spatial resolution because at 30° eccentricity, the resolution threshold is less than 1° (Wertheim, 1891; Mandelbaum and Sloan, 1947; Weymouth, 1958; Frisen and Glansholm, 1975; Rovamo and Virsu, 1979). The rise could also not be caused by spatial interference, because spatial interference occurs in separation discrimination tasks only when at least one target is flanked on both sides by other targets (Westheimer, Shimamura, and McKee, 1976; Badcock and Westheimer, 1985a and b; Yap, Levi, and Klein, 1989). In subsequent experiments we investigate how the eccentricity effect evident in these data depends on the spatial and temporal characteristics of the targets, and on their separation.

II Separation Effects for Fixed Eccentricities

The data of Figs. 1 and 2 show thresholds increasing only slightly as the eccentricity is changed from 2° to 10°. This suggests that, in that range, separation is the primary determinant of the slope of the Weber function for separation discrimination. To extend our understanding of how separation and eccentricity contribute to separation discrimination thresholds over a larger range of values, we measured separation discrimination thresholds for stimuli presented on isoeccentric arcs at 2.5°, 5° and 10° eccentricity on the nasal retina of the right eye. Prior to that, we replicated the traditional Weber function for separation using fovea-centered stimuli.

The targets were rectangles, 4 arcmin high by 32 arcmin long, presented for 150 ms (for consistency with Levi et al., 1988). We used several viewing distances: 212 cm, 106 cm and 53 cm. For 2.5° eccentricity, we used 212 cm for the two smallest separations and 106 cm for the other separations. For 5° eccentricity, we used 106 cm for the 1.4° separation and 53 cm for the other separations. For 10° eccentricity, we used 53 cm for all separations. The overall vertical position of the stimulus was changed from trial to trial by an amount that varied with eccentricity. At 2.5° eccentricity, this vertical displacement was ±0.17° for the two smallest separations and ±0.35° for the other separations. At 5° eccentricity, the displacement was ±0.35° for the separation of 1.4° and ±0.7° for the other separations. At 10° eccentricity, it was ±0.7° for all separations. Eccentric viewing was achieved by having the observer fixate a line placed an appropriate distance from the stimuli. Two observers were tested at each eccentricity.

Data obtained with fovea-centered stimuli, replicating the standard result, are shown in Fig. 3. The data from each observer were fitted with straight lines on log-log coordinates using a program that weighted each threshold by its inverse variance and minimized chi square. Slopes for the data of the two observers were 0.9 ± 0.1 and 0.7 ± 0.2 with chi squares (6 degrees of freedom) of 8.7 and 33.5, respectively. The slope obtained for Observer AM is somewhat shallow and has a larger error primarily because the relatively large error bar for the smallest separation

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diminished its contribution to the slope. (A line drawn by eye has a steeper slope.) For the other observer, we were able to replicate the classical result under our stimulus conditions. We conclude that our stimulus conditions are within the standard range. Subsequent comparison of our results with data from another laboratory supports this conclusion.

Data obtained with stimuli presented on isoeccentric arcs are shown in Fig. 4. For separations less than about 5° at all eccentricities, and for separations less than 10° at 10° eccentricity, the thresholds increase markedly with separation under these isoeccentric conditions. Slopes of 0.5 to 0.7 on log-log axes were obtained at all eccentricities. The individual slopes are shown in Table 1. These values are similar to the slopes of 0.6 to 0.7 obtained with 3-dot bisection for eccentricities of 0° to 10° (Yap, Levi, and Klein, 1987). Eccentricity also had a small but significant effect in this separation-dependent region. These results are consistent with those of 3-dot bisection (ibid.), and 2-dot separation discrimination for a range of smaller separations (Yap et al., 1989) and with our finding, reported above, that eccentricity has a small effect over a wide range of separations.

For separations larger than 6° at 5° eccentricity and larger than 10° at 10° eccentricity, the thresholds lose their dependence on separation, as evidenced by the flattening of the curves. In this separation-independent region, eccentricity has a much larger effect than it has in the separation-dependent region.

We know that the flattening was not caused by edge effects because the 5° and 10° data were obtained at the same viewing distance, and yet those two curves begin to flatten at quite different separations. It appears that the process underlying separation discrimination thresholds at relatively large separations and eccentricities has characteristics quite different from those of the process underlying separation discrimination thresholds at smaller angles. This could be attributed to a single mechanism, whose properties change, or to two mechanisms, one quite sensitive to separation and only somewhat sensitive to eccentricity, and the other quite sensitive to eccentricity

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and insensitive to separation.

Our isoeccentric data obtained at 2.5° eccentricity differ in shape from our other isoeccentric data and therefore require particular attention. To provide a further check on these results, we obtained data from a third observer, PA. The 2.5° eccentricity data for all three observers are shown in Fig. 5. At this eccentricity, the function did not flatten for any of the three observers tested. Its slope did decrease significantly as separation increased for observer PA.

The flattening that occurs in our isoeccentric data is roughly consistent with the results reported by Levi et al. (1988). They found, however, that there was no effect of separation for separations from 3.5 to 10°, except for a decrease in threshold at 10° separation. There are significant differences between our experiments and theirs that may account for this discrepancy. Most important is the fact that Levi et al. (1988) used a three-dot bisection task in which the eccentricity of the middle dot decreased as the separation increased. They attributed their decrease in threshold at 10° separation to the small eccentricity of the middle dot. In general, the effect of increasing separation in their paradigm may have been partly concealed by the opposite effect of decreasing the eccentricity of the middle dot. This suggestion is supported by the observation that for Observers DL (Levi et al., 1988) and YLY (ibid. and the present study), the threshold versus separation function at 10° eccentricity begins to flatten at 3.5° for three-dot bisection whereas for two-dot separation discrimination it begins to flatten at 8° to 10°.

Levi and Klein (1989, unpublished) have also collected some separation discrimination data on isoeccentric arcs. For comparison we show our data and theirs together in Fig. 6. (The Levi and Klein data were divided by 0.675 to compensate for the fact that they report the 75% level and we report the 84% level on the psychometric function.) The overall agreement between the results from the two laboratories is excellent. At 2.5° eccentricity [Fig. 6(a)] the agreement between the data of our three observers and their observer is remarkable up to a separation of 3°. For larger separations at this eccentricity, the Levi and Klein data show a flattening and ours do not. On the

other hand, at 5° eccentricity [Fig. 6(b)], the data of Levi and Klein increase monotonically with separation whereas our data show an obvious flattening for separations larger than 6°. At 10° eccentricity [Fig. 6(c)], both sets of data flatten at large separations, although the data of Levi and Klein begin to flatten at a slightly smaller separation. Although the flattening may not be robust at 2.5° or 5°, we can conclude that, regardless of the eccentricity, separation discrimination thresholds depend primarily on separation when the separation is small (separation ≤ eccentricity), and can be completely independent of separation when the separation is large, particularly if the eccentricity is also large.

III   Spatial and Temporal Characteristics of the Targets

The data shown in Figs. 1 and 2 suggest that the effect of eccentricity may depend on the spatial or temporal characteristics of the targets, and the strength of this dependence may vary with the separation used. To investigate this hypothesis, we conducted further tests of the effects of these parameters.

Exposure Duration Effects

For fovea-centered stimuli, the slope of the Weber function depends on exposure duration (Burbeck, 1986; Yap et al., 1987). The threshold at small separations is higher for a 100-ms exposure duration than for a 500-ms or 1-s duration; thus, the slope is shallower for brief durations than for long ones. To understand more about the temporal factors contributing to the slope of the Weber function for separation, we measured separation discrimination thresholds at an eccentricity of 10° using two exposure durations and a range of separations. For separations larger than 1° (Observer JGP) and larger than 0.5° (Observer CAB), the targets were the same as in the first experiment (bars 1.3° x 1.1°). For the smaller separations, the targets were lines 0.017° x 1.1°. Data from this experiment are shown in Fig. 7. For Observer CAB, there was an effect of

exposure duration when the lines were used at 0.5° and 0.8°. Otherwise there was no significant effect of exposure duration.

Although the performance of Observer JGP improved with increasing duration at large separations, the 500-ms function was actually shallower than the 100-ms function. We have no explanation for this effect. Yap et al. (1987) also found a smaller effect of duration at 10° eccentricity than at 0° for the three-dot bisection task. However, the was the same for all separations tested. The difference between our present results and the results of Yap et al. (1987) may reflect a difference in approach: whether the observer takes time to ponder over the decision. We have noticed that observers show much less dependence on duration if they pause before deciding rather than responding immediately.

In general, we found that at 10° eccentricity, exposure duration had only a small effect on the slope of the Weber function for separation discrimination for either observer. For fovea-centered targets, duration affects the slope only at separations < 20 arcmin (Burbeck, 1986). Thus, exposure duration does not appear to be a major factor controlling the slope of the Weber function, provided spectrally broadband, high-contrast targets are used.

Target Size

We now turn to the spatial domain to determine whether target size is an important contributor to the Weber function for separation discrimination. We used lines that were 4 arcmin wide and varied the length from 2 arcmin to 120 arcmin. Exposure duration was 150 ms. All other details of the experiment were unchanged.

Fig. 8 shows the effect of length on separation discrimination thresholds for a 1° separation at 0.5° and 10° eccentricity and for a 5° separation at 10° eccentricity. For the 1° separation, there was an interaction between the length effect and the eccentricity. Increasing length improved thresholds significantly at 10° eccentricity but had no effect at 0.5° eccentricity. Line length also

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had a significant effect on threshold for a 5° separation at 10° eccentricity, but the effect was smaller than for the 1° separation at this eccentricity. The data suggest that the size of the separation relative to the eccentricity is an important factor in the length effect. Larger line length effects are found when the separation is small relative to the eccentricity.

The results of these line-length experiments have implications for the primary focus of this study, namely the roles of eccentricity and separation in the Weber function for separation discrimination. In the experiments on the effects of eccentricity for fixed separation stimuli, we found pronounced eccentricity effects in the 15° to 30° eccentricity range. The slope of the function was steeper with small targets [compare Fig. 1 with Fig. 2], and with a small separation [compare Fig. 2(a) with Fig. 2(b)]. This dependence on target size and separation, together with the results of the line-length experiments showing an interaction between separation and eccentricity, suggests that even the large targets may not have been large enough at 15° to 30° eccentricity. Thus, the eccentricity effects shown in Fig. 1 may include length effects.

The line-length data confirm that the lines used in our isoeccentric study were long enough that length was not a limiting factor. That study was limited to eccentricities ≤ 10°.

The problem of how to scale targets appropriately for positional tasks has received much attention in recent years (Levi, Klein, and Aitsebaomo, 1985; Watson; 1987; Virsu, Nasanen, and Osmoviita, 1987; Yap et al., 1987; Toet, Snippe, and Koenderink, 1988). The results of our experiments indicate that scaling the targets according to a given factor, as proposed by the above studies, e.g., according to the cortical magnification factor, does not necessarily solve the scaling problem because the effect of target size at a given eccentricity depends on the separation being tested.

Levi, Klein, and Yap (1987) found that for a separation of 0.2° at 2.5° eccentricity, three-dot bisection and two-dot separation discrimination thresholds are reduced when more stimulus samples are provided. Our line-length results indicate that such improvement occurs only

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when the separation is small relative to the eccentricity. When it is relatively large, threshold is independent of line length. In general, the line length results indicate that the slope of the Weber function depends on the target size only when the separation is small relative to the eccentricity.

IV Discussion

The data reported here suggest that there may be two ways to make spatial interval discriminations. When the separation is less than the target eccentricity, the discrimination process depends primarily on target separation and secondarily on eccentricity. When the separation is larger, the process depends primarily (perhaps exclusively) on target eccentricity. What is the nature of these processes? Levi et al. (1988) attribute the small-separation data to the responses of local spatial filters and the large-separation data to a "cortical ruler," i.e., a process that measures the cortical distance between the targets, as though with a ruler.

There are data to suggest that neither of these explanations is fully adequate. The separation-dependent region probably includes all very small separations, certainly all those that fall within the fovea itself, but the local spatial filter model cannot account for the failure of extraneous flanking lines to affect thresholds for such small separations (Morgan and Ward, 1985). The local-spatial-filters model also does not fully account for the increase in threshold with separation. For isoeccentric targets, threshold increases approximately as $s^{0.65}$, where s is the mean target separation. A filter model in which error scales with receptive field size predicts that the threshold will increase as s^1.

To deal with some of the problems posed by local-spatial-filter models, Morgan and Regan (1987) have proposed an alternative scheme. They suggest that there is "a plurality of coincidence detectors with different receptive field separations, and two-line interval discrimination depends on the relative activity of the different coincidence detectors." This hypothesis is, or can be readily be

made to be, consistent with the insensitivity of separation discrimination thresholds to the contrast and spatial frequency content of the targets, but it requires a large number of units, each dedicated to a single task. Also, the hypothesis provides no natural way to account for the increase in threshold with increasing target separation, an especially serious drawback.

We suggest the following alternative explanation for thresholds in the separation-dependent region. A plausible method for calculating separations between targets is to step from one target to the other, counting the steps as one goes, as proposed in a more general context by Fullerton and Cattell (1892). If each step has equal error and the steps are independent, then the Δx vs. x function will have a slope of 0.5 on log-log scales. Our data are clearly steeper than that. However, if the steps are not independent but positively correlated, the slope will be larger than 0.5. If the steps are perfectly correlated, the slope will be 1.0. If there is some correlation, the slope will lie between 0.5 and 1.0 (Laming, 1986), as we find. In this context, a slope of 0.65 is consistent with a model in which the errors in the individual steps are slightly correlated.

The step-increment approach has physiological plausibility. It has been rejected in the past because it yields too low a slope, unless one assumes nearly perfect correlation between the errors, which is physiologically implausible. The smaller slopes obtained with the isoeccentric targets make this approach worth reconsidering. Although other models could also be compatible with these new data, it seems worth noting that the incremental step is again viable.

We now consider the separation-independent region. Morgan and Regan's coincidence-detector model is able to account for the data in this region better than it can in the small-separation region, because their model has no natural dependence on separation. However, the requirement that there be many dedicated units continues to pose a problem.

Another candidate model is the "cortical ruler" hypothesis of Levi et al. (1988). It has the property that thresholds depend only on eccentricity and not on separation, as this region requires. However, it also has other implications which are not confirmed. If one interprets literally the

hypothesis that separations are encoded as cortical distances, then perceived separation should decrease with increasing eccentricity at a rate predicted by the cortical magnification factor. Assuming an x-intercept of -0.6° (equivalent to the eccentricity at which the foveal threshold doubles), perceived separation should then decrease by a factor of 17 when the target moves from the fovea to 10° eccentricity. A long history of research on the change in perceived size with eccentricity (e.g., Schneider, Ehrlich, Stein, Flaum, and Mangel, 1978) shows that this prediction is not fulfilled. Perceived size changes much more slowly with eccentricity than predicted by the change in cortical distance. (Under our experimental conditions, perceived separation decreased by about 20% between 0 and 10° eccentricity.)

Another objection to the cortical ruler hypothesis is that when the targets are located on either side of the visual midline, the perceived separation is essentially the same as when the targets are in the same hemifield, yet in terms of cortical distance, the stimuli are dramatically different. Thus, taken literally, the cortical ruler hypothesis does not seem to be consistent with some basic facts about the perception of separation (for example, see Paradiso, Carney, and Freeman, 1989). A different type of mechanism is required to account for the separation-independent data, one that is explicitly not sensitive to the cortical distance between the targets.

We propose the following alternative: for relatively large separations, the best information about target separation may be contained in a fovea-centered polar representation. In such a representation, the separation between targets on an isoeccentric arc is represented by an angle. The accuracy with which the angle is encoded depends exclusively on the eccentricity of the targets. As the eccentricity increases, the precision with which the targets define the angle decreases. The positions of the individual targets are known with less accuracy, and more importantly, the distance between the targets and the fovea is greater so there is more opportunity for the information to be degraded. If the accuracy with which two angles can be discriminated depends primarily on the accuracy with which each angle is represented, then the discrimination

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threshold would be independent of separation, but would depend heavily on eccentricity. Thus, this model can account for the fact that eccentricity plays a larger role in the separation-independent region than in the separation-dependent region. In the separation-dependent region, thresholds are elevated because the local positional information is degraded. In the separation-independent region, thresholds are further degraded because the increased distance to the fovea degrades the quality of information in the fovea-centered polar representation. A problem with this model is that it does not apply to the condition in which the targets are centered about the fovea. In that case, the observer must judge the distances to the targets.

Although we were unable to invent a mechanism within this scheme to predict when the transition between the separation-dependent and the separation-independent regions should occur, we find it interesting that the transition occurs at a constant angle in the polar-coordinate representation. Our data and those of Levi and Klein (1989) show a transition at about 50°. Thus, the model at least adds parsimony to the description of the data. It also suggests that there may be a connection between the representation used to discriminate between large separations and the representation used to direct saccades, which presumably is also fovea-centered.

The possibility that there are two qualitatively different mechanisms underlying separation-discrimination thresholds requires that we reexamine many conclusions that have been drawn about the separation-discrimination mechanism. For example, the fact that separation-discrimination thresholds are unaffected by large changes in the spatial-frequency content of the targets (Toet et al., 1987; Burbeck, 1987, 1988a) has served as an argument against the local-spatial-filters model of separation discrimination. However, all of the targets used in those studies were fovea-centered and many had separations that were large enough to place the targets off the fovea. Under those conditions, one cannot be certain that the stimuli lie in the separation-dependent region. Thus these studies may actually be investigations of a separation-independent process. The possibility that there are two mechanisms of separation

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discrimination may require the reanalysis of many such results.

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Figure Captions

Fig. 1   Separation discrimination thresholds plotted as a function of eccentricity for a separation
         of 4.2° for observers JGP and RLW. Targets used were bars 1.3° long and 1.1° tall
         lasting 500 ms. Thresholds show little dependence on eccentricity up to 10° or 15°. For
         larger eccentricities, the eccentricity effect was pronounced.

Fig. 2   Separation discrimination thresholds plotted as a function of eccentricity for a separation
         of 2.9° (a) and 5.9° (b) for Observers JGP and RLW. Targets used were rectangles 50
         arcmin long and 4.1 arc min tall lasting 200 ms. For the separation of 2.9°, thresholds
         were constant up to 10° eccentricity and increased for larger eccentricities. For the
         separation of 5.9°, thresholds showed a slight dependence on eccentricity at all
         eccentricities for Observer RLW but a steeper slope for eccentricities greater than 15° for
         Observer JGP.

Fig. 3   Separation discrimination thresholds for fovea-centered stimuli plotted as a function of
         separation on log-log axes for Observers YLY and AM. Targets used were rectangles 32
         arcmin long and 4 arcmin tall. The slopes of the best-fitting lines were 0.9 for observer
         YLY and 0.7 for Observer AM, which follow Weber's Law behavior closely.

Fig. 4   Separation discrimination thresholds plotted as a function of separation at eccentricities of
         2.5°, 5° and 10° for observers YLY (a) and AM (b). Targets used were rectangles 32
         arcmin long and 4 arcmin tall, placed on isoeccentric arcs with a radius equal to the
         appropriate eccentricity. For both observers, thresholds depend on separation for

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separations smaller than 5°. However, for separations larger than 5° at 5° eccentricity, and larger than 10° at 10° eccentricity, threshold becomes a constant function of separation, depending only on eccentricity (stippled connections).
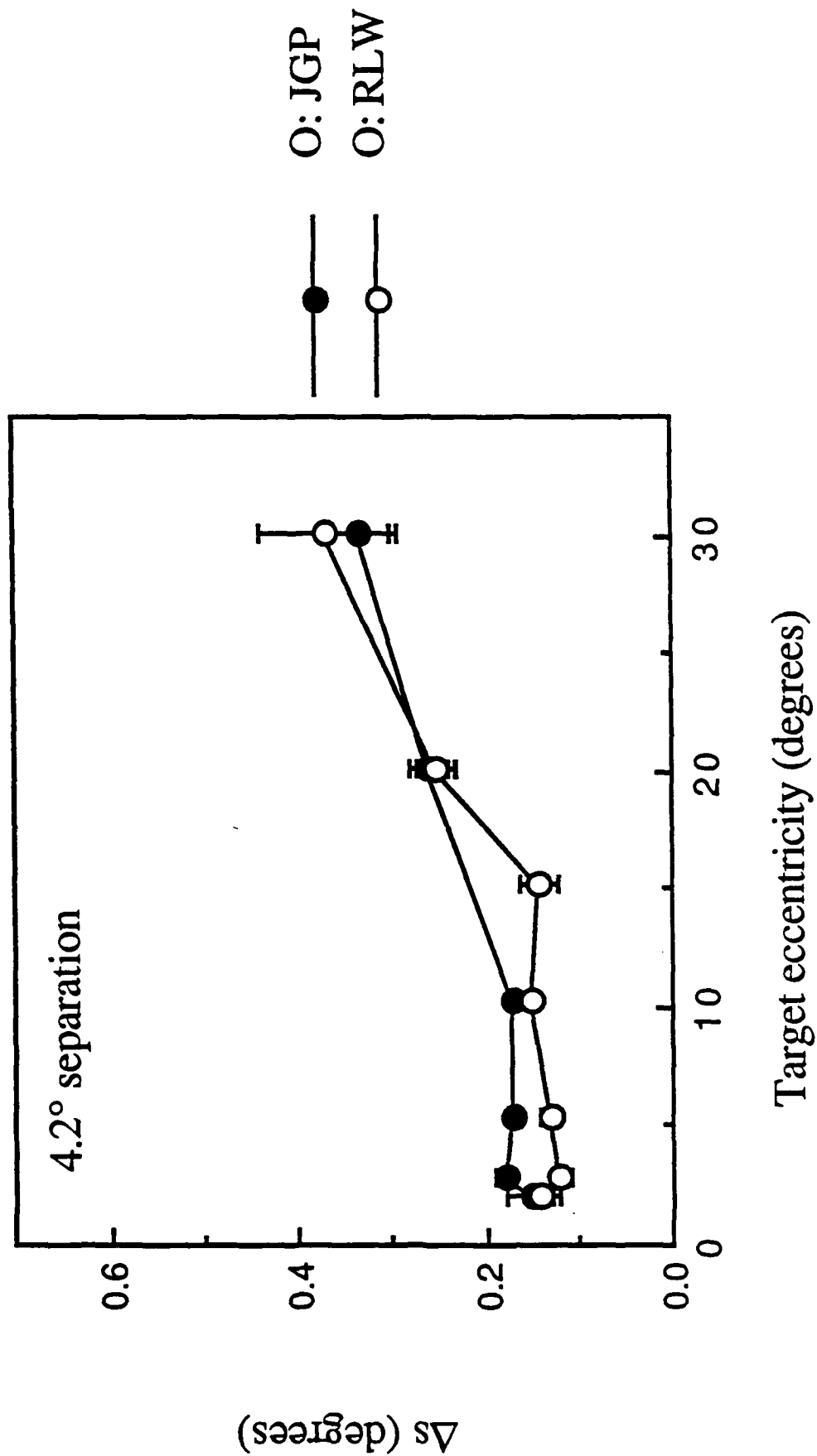
Fig. 5   Separation discrimination thresholds plotted as a function of separation at an eccentricity of 2.5° for Observers YLY, AM and PA. Targets used were rectangles 32 arcmin long and 4 arcmin tall, placed on an isoeccentric arc with a radius of 2.5°. Thresholds increase with increasing separation for all separations, although the slope decreases significantly for separations greater than 2° for Observer PA.

Fig. 6   Separation discrimination thresholds obtained with isoeccentric targets plotted on log-log axes as a function of separation at an eccentricity of 2.5° (a), 5° (b) and 10° (c) for observers YLY, AM and PA and Observer DL from Levi and Klein (1989). The Levi and Klein (1989) data, which were determined at the 75% correct level, have been divided by .675, to allow comparisons to be made at an 84% correct level. The standard errors (approximately 10% of the thresholds) have not been shown for the sake of clarity. At 2.5° eccentricity, the functions of our three observers did not flatten whereas the function for Observer DL did, while at 5° eccentricity, our data flattened but those of Observer DL did not. At 10° eccentricity, both sets of data show a range of separations where the thresholds are independent of separation, but the ranges differ somewhat.
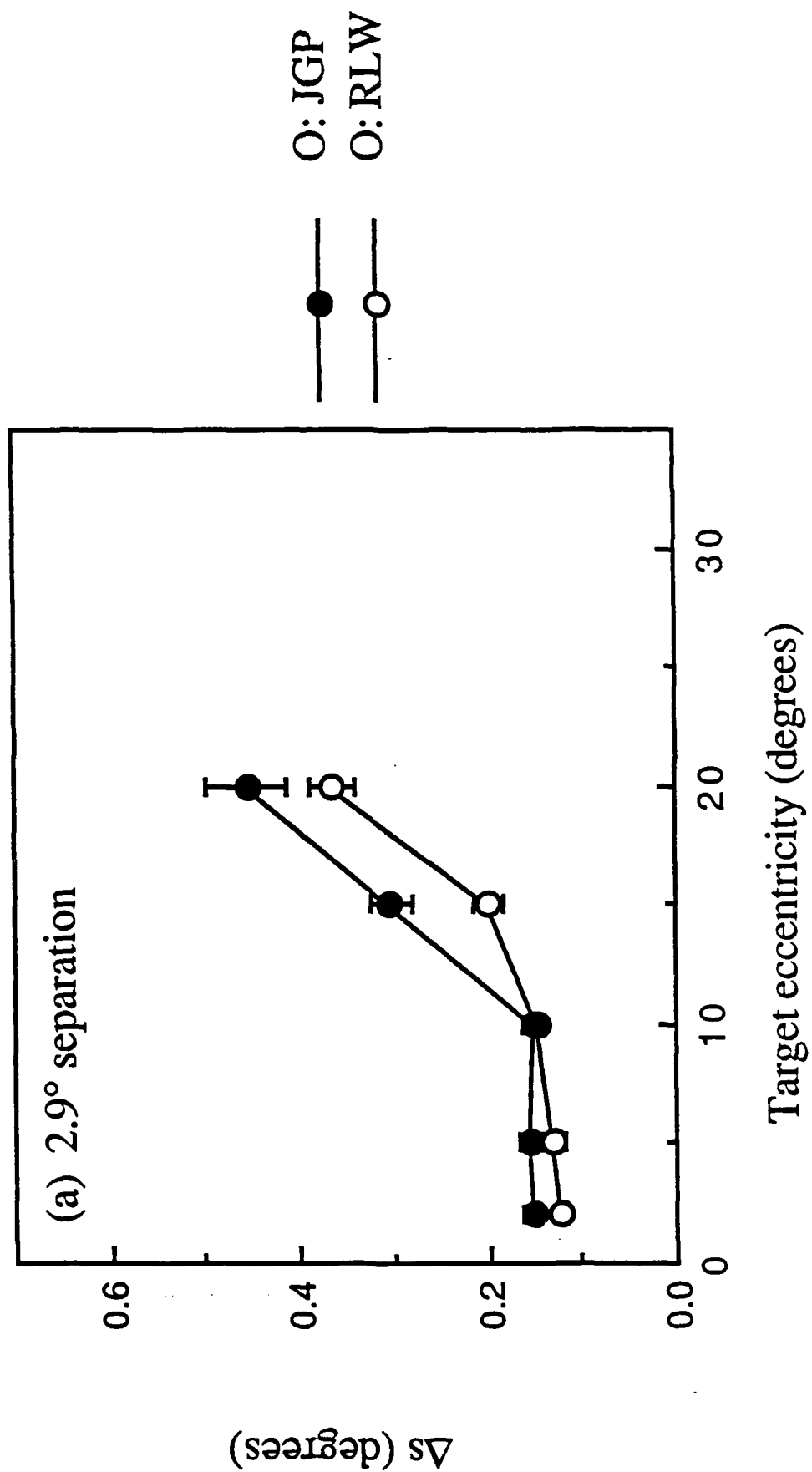
Fig. 7   Separation discrimination thresholds plotted as a function of separation for exposure durations of 100 and 500 ms at an eccentricity of 10° for Observers CAB (a) and JGP (b). Targets used were bars 1.3° long and 1.1° tall. Observer CAB did not show any significant difference between the two exposure durations. Although Observer JGP

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obtained better thresholds in general with a 500-ms exposure than with a 100-ms exposure, he showed a flatter slope with the 500-ms than with the 100-ms exposure.
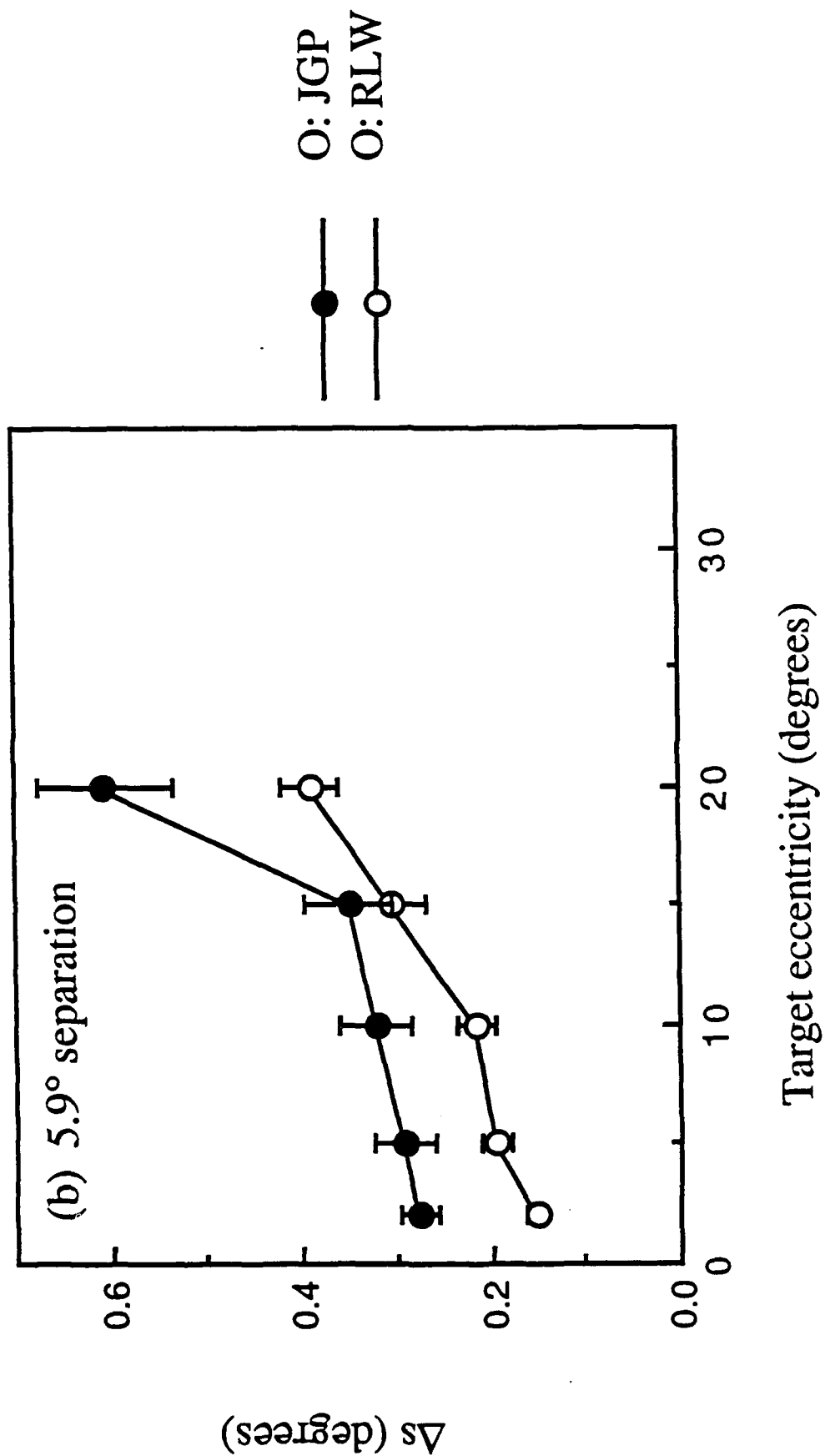
Fig. 8   Separation discrimination thresholds plotted as a function of target length for targets with a height of 4 arcmin for a separation of 1° at 0.5° and 10° eccentricity and for a separation of 5° at 10° eccentricity for Observers JB (a) and DH (b). Exposure duration was 150 ms. Thresholds improved sharply with increasing target length for the separation of 1° at at 10° but not for the separation of 1°at 0.5° eccentricity nor for the separation of 5° at 10° eccentricity.

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Fig. 1

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(a) 2.9° separation

O: JGP
O: RLW

Δs (degrees)

Target eccentricity (degrees)

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Fig. 2a

(b) 5.9° separation

O: JGP
O: RLW

Target eccentricity (degrees)

Δs (degrees)

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Fig. 2b

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O: YLY
$\log(\Delta s) = .9 \log(s) - 1.2$

O: AM
$\log(\Delta s) = .7 \log(s) - 1.1$
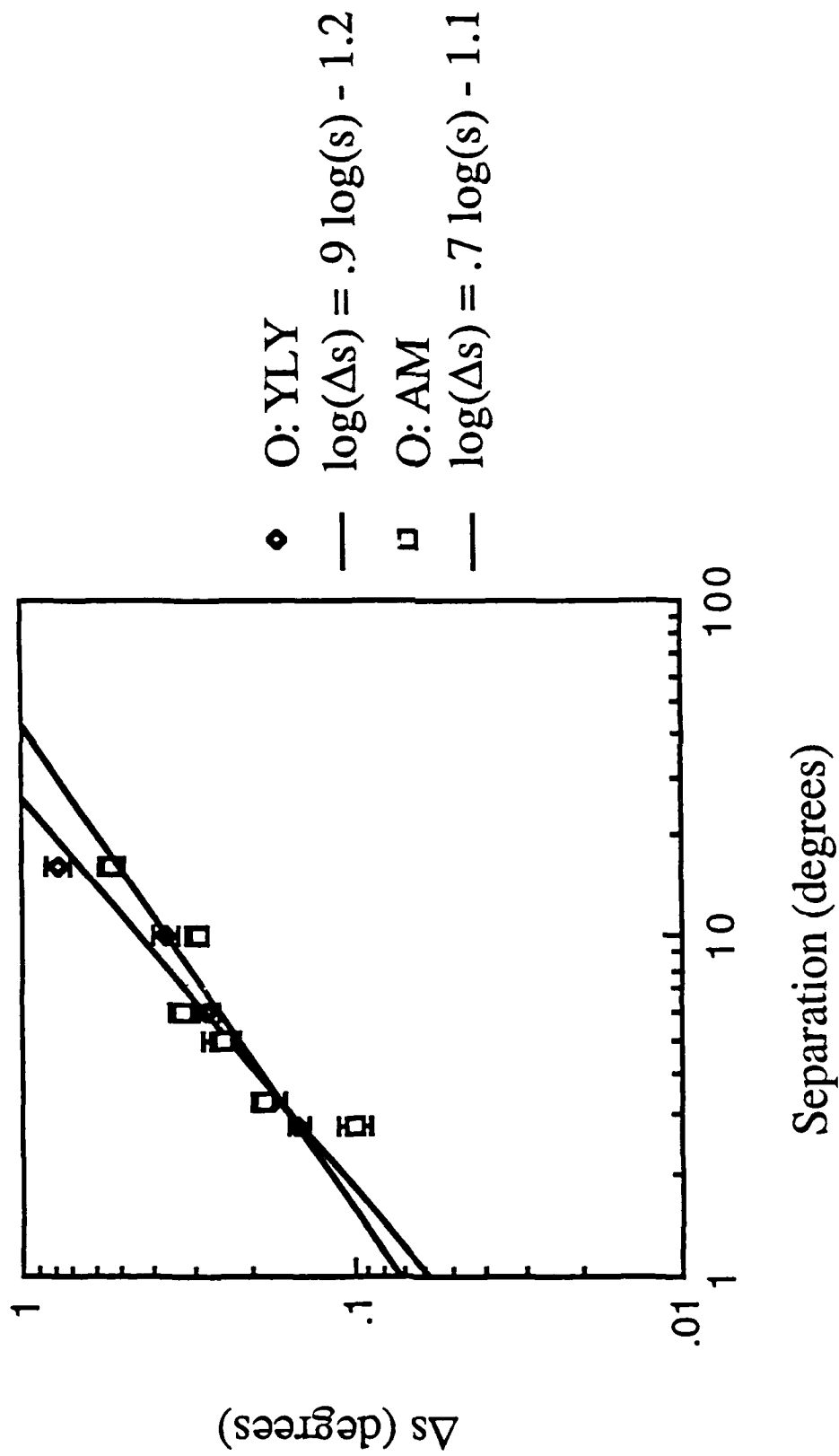
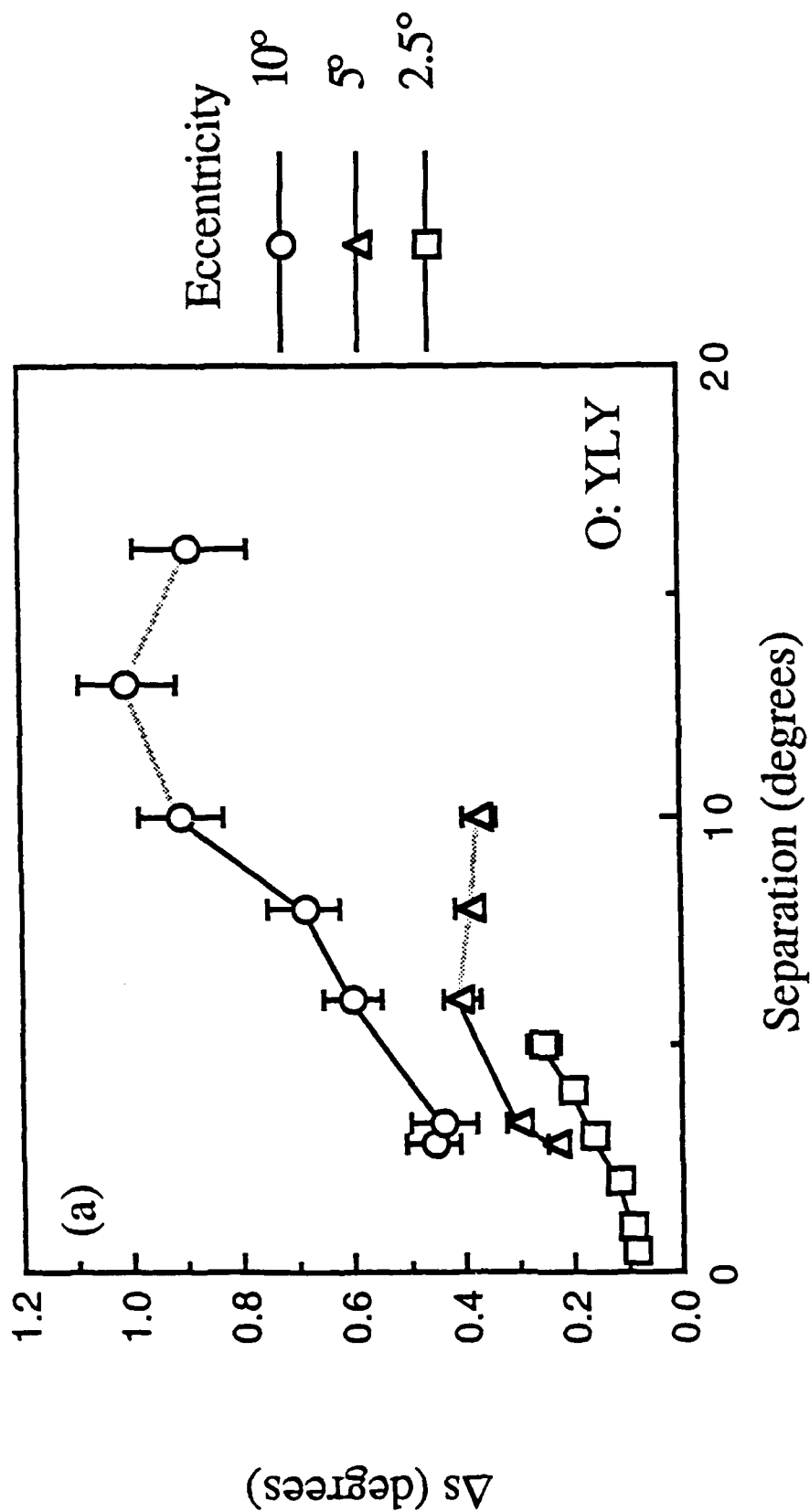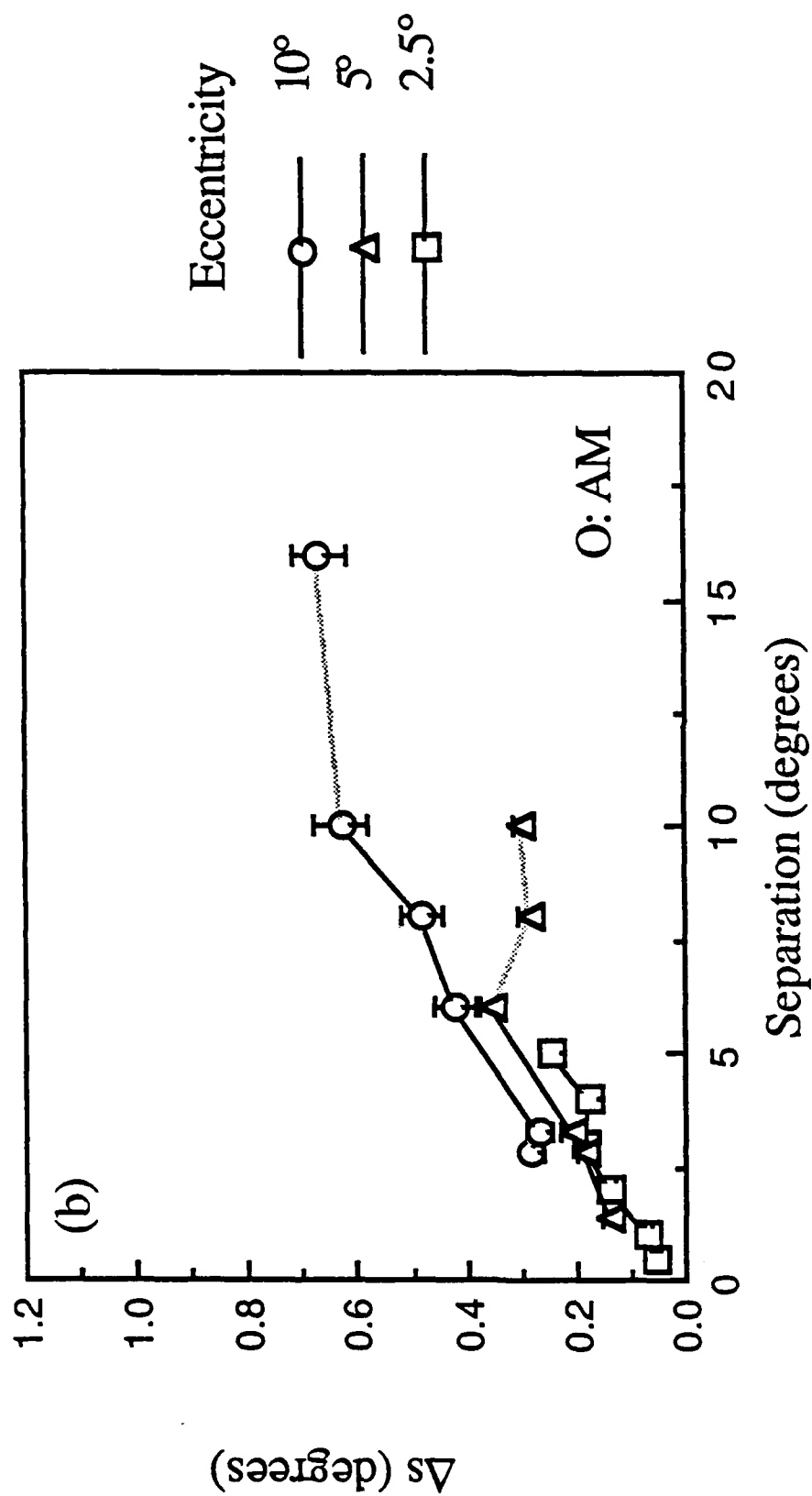Separation (degrees)

Δs (degrees)

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Fig. 3

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Fig. 4a

Eccentricity

○ 10°
△ 5°
□ 2.5°

(b)

O: AM

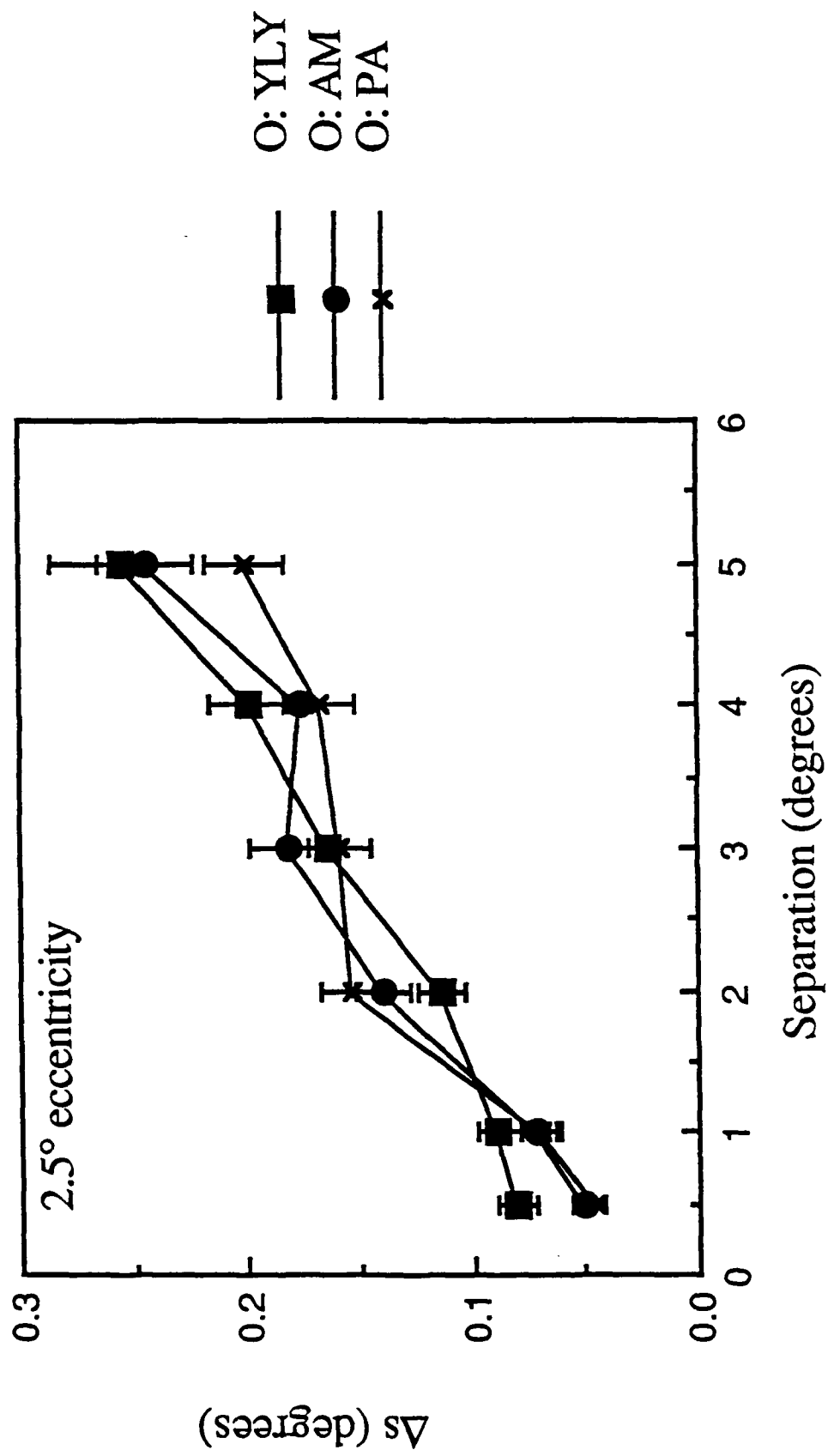Separation (degrees)

Δs (degrees)

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Fig. 4b

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Fig. 5

(a) 2.5° eccentricity

O: YLY
O: AM
O: PA
Levi&Klein

Separation (degrees)

Δs (degrees)

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Fig. 6a

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(b) 5° eccentricity

O: YLY
O: AM
Levi&Klein

Separation (degrees)

Δs (degrees)

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Fig. 6b

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(c) 10° eccentricity

O: YLY
O: AM
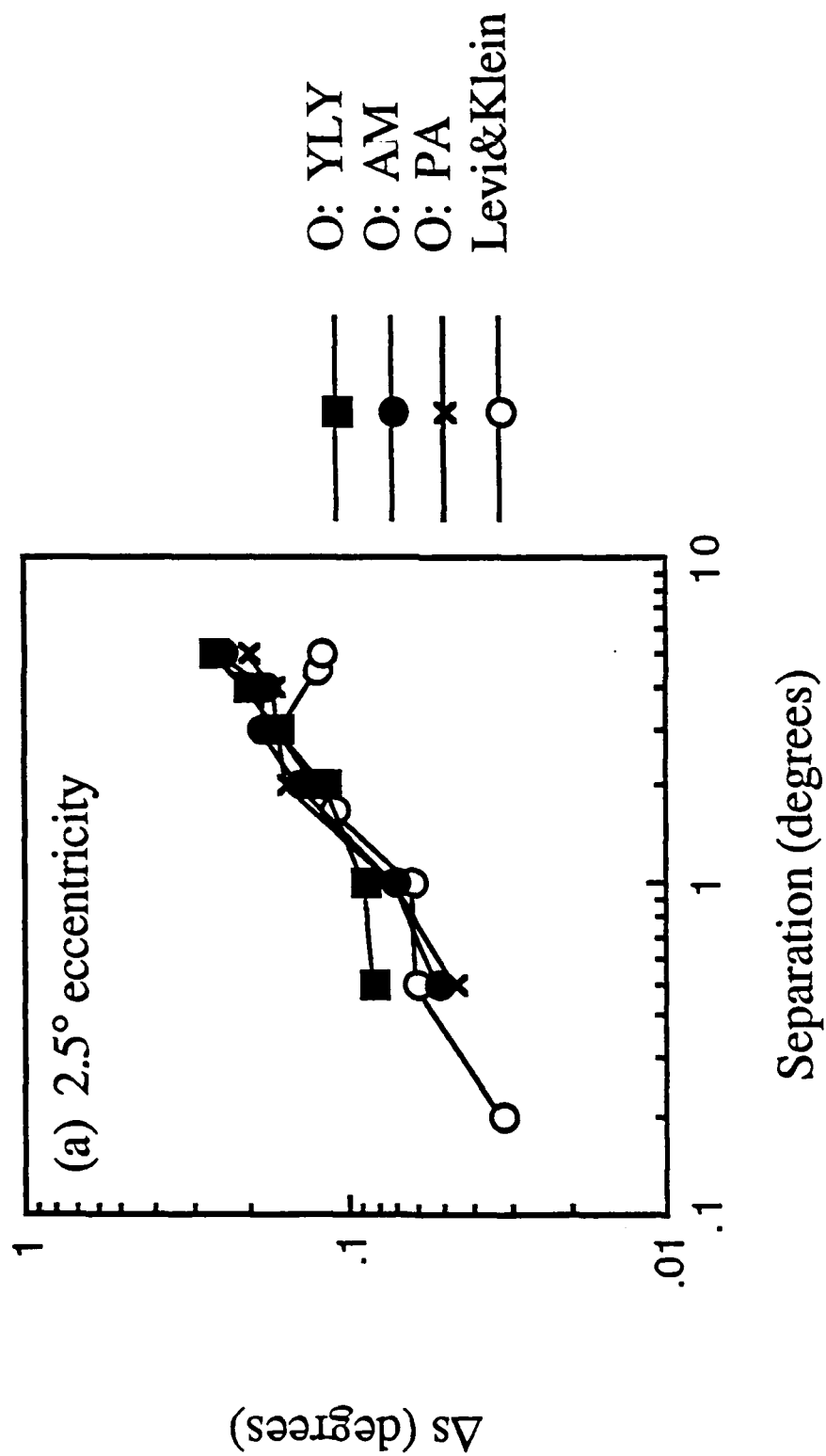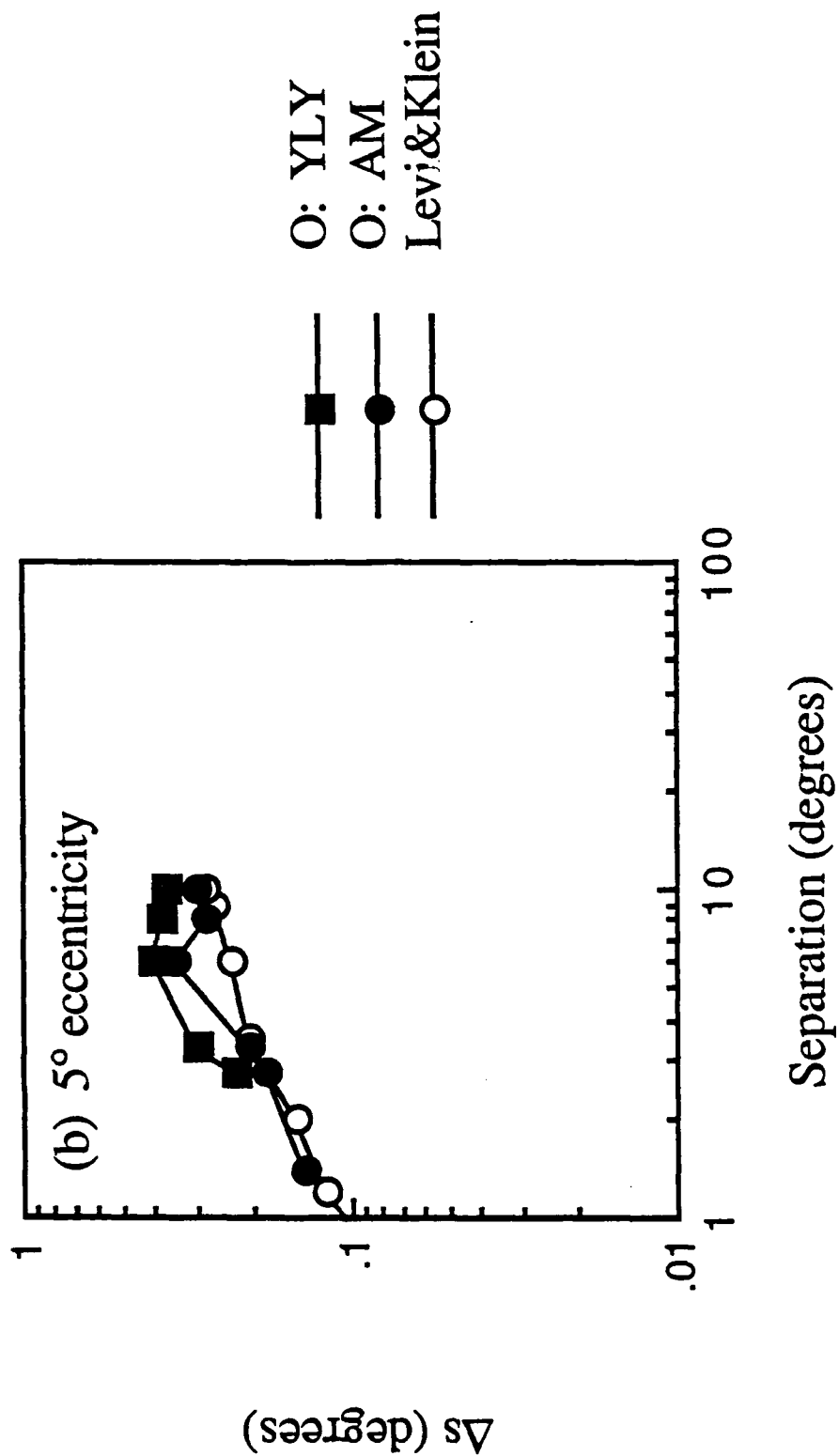Levi&Klein

Separation (degrees)

Δs (degrees)

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Fig. 6c

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"Two Mechanisms for Localization?"
Fig. 7a

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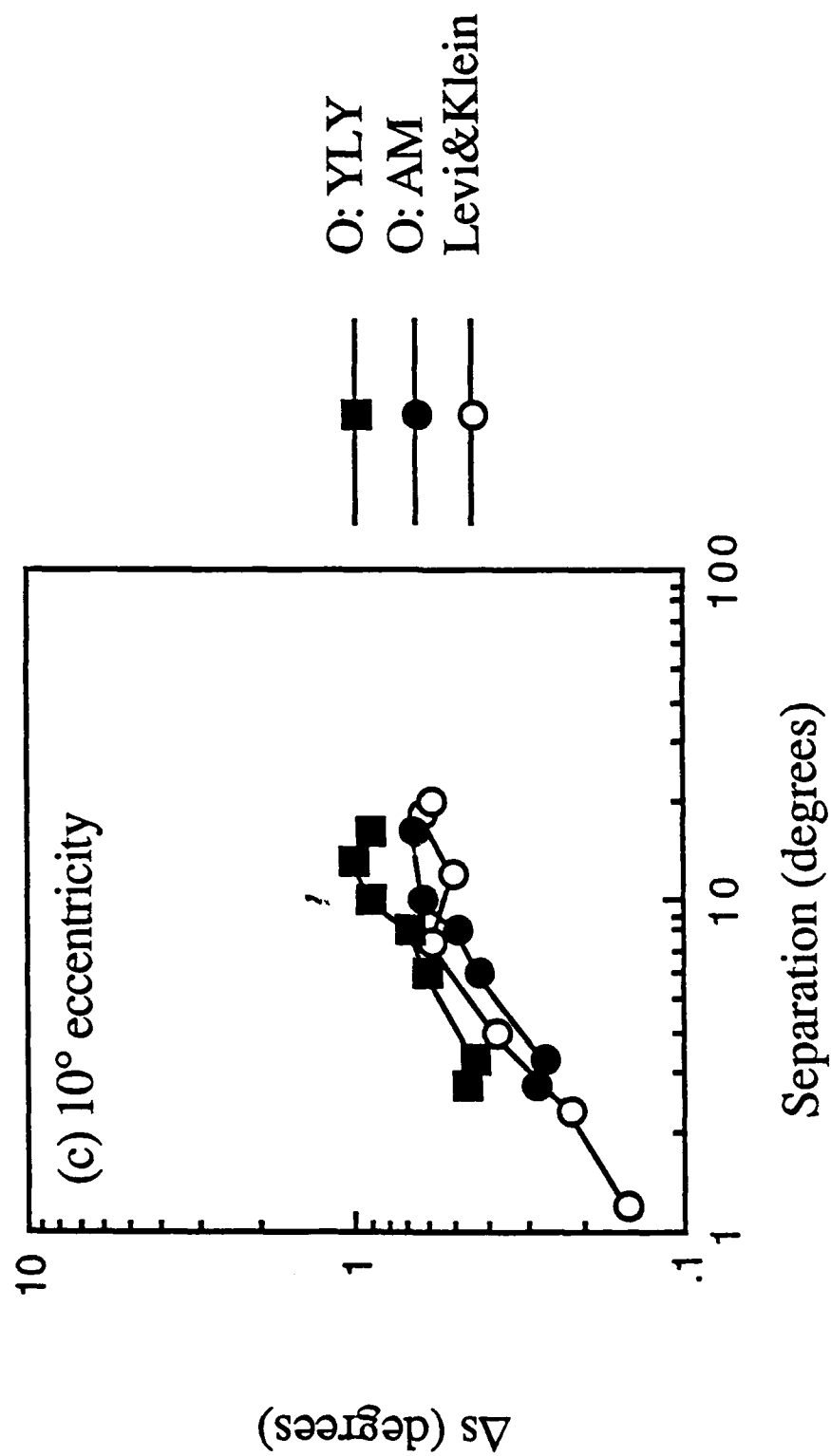"Two Mechanisms for Localization?"
Fig. 7b

Legend:
- $5° @ 10°$ (△)
- $1° @ 10°$ (○)
- $1° @ 0.5°$ (●)

(a)

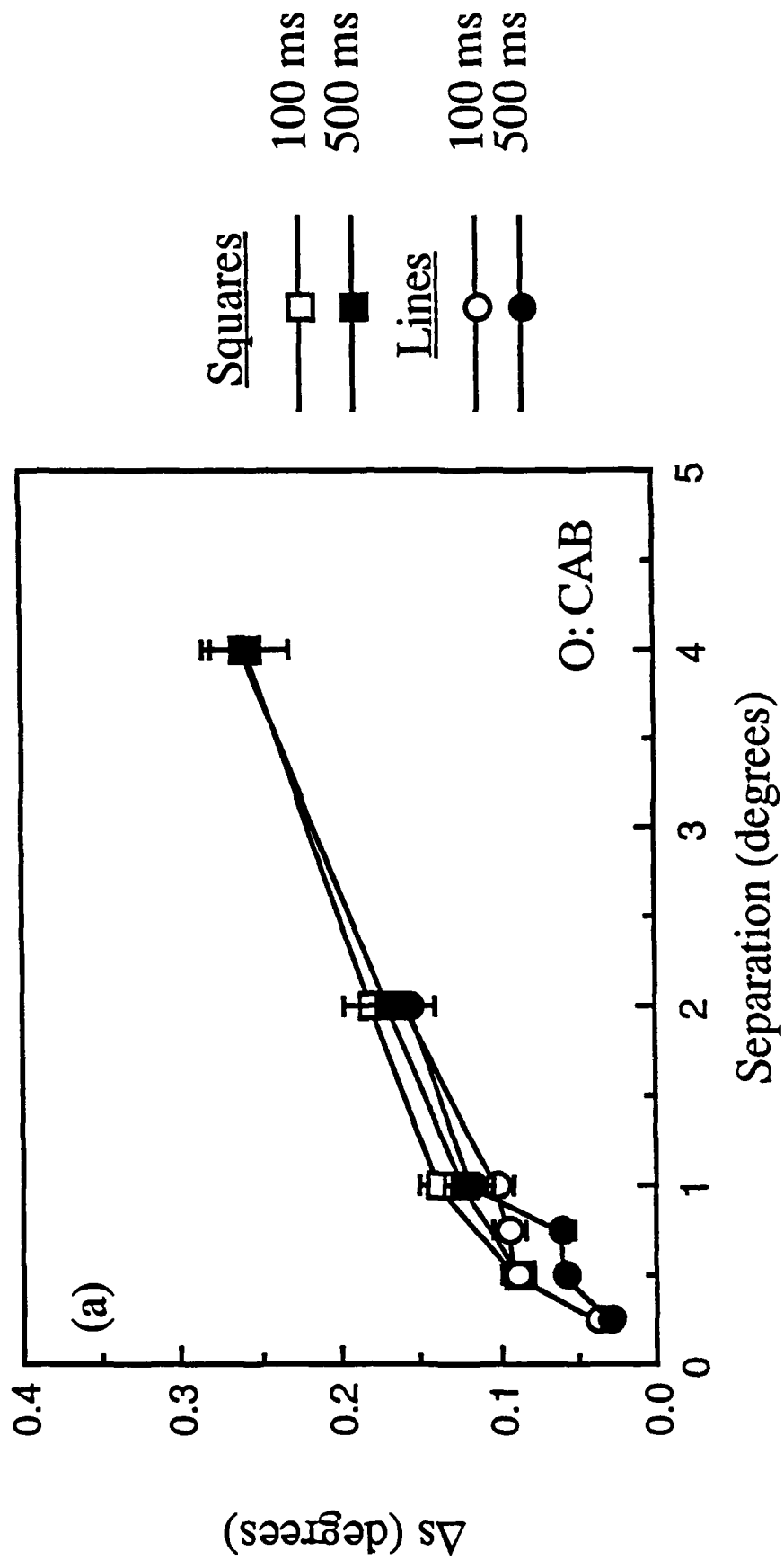Δs (arcmin) vs Length (arcmin)

O: JB

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"Two Mechanisms for Localization?"
Fig. 8a

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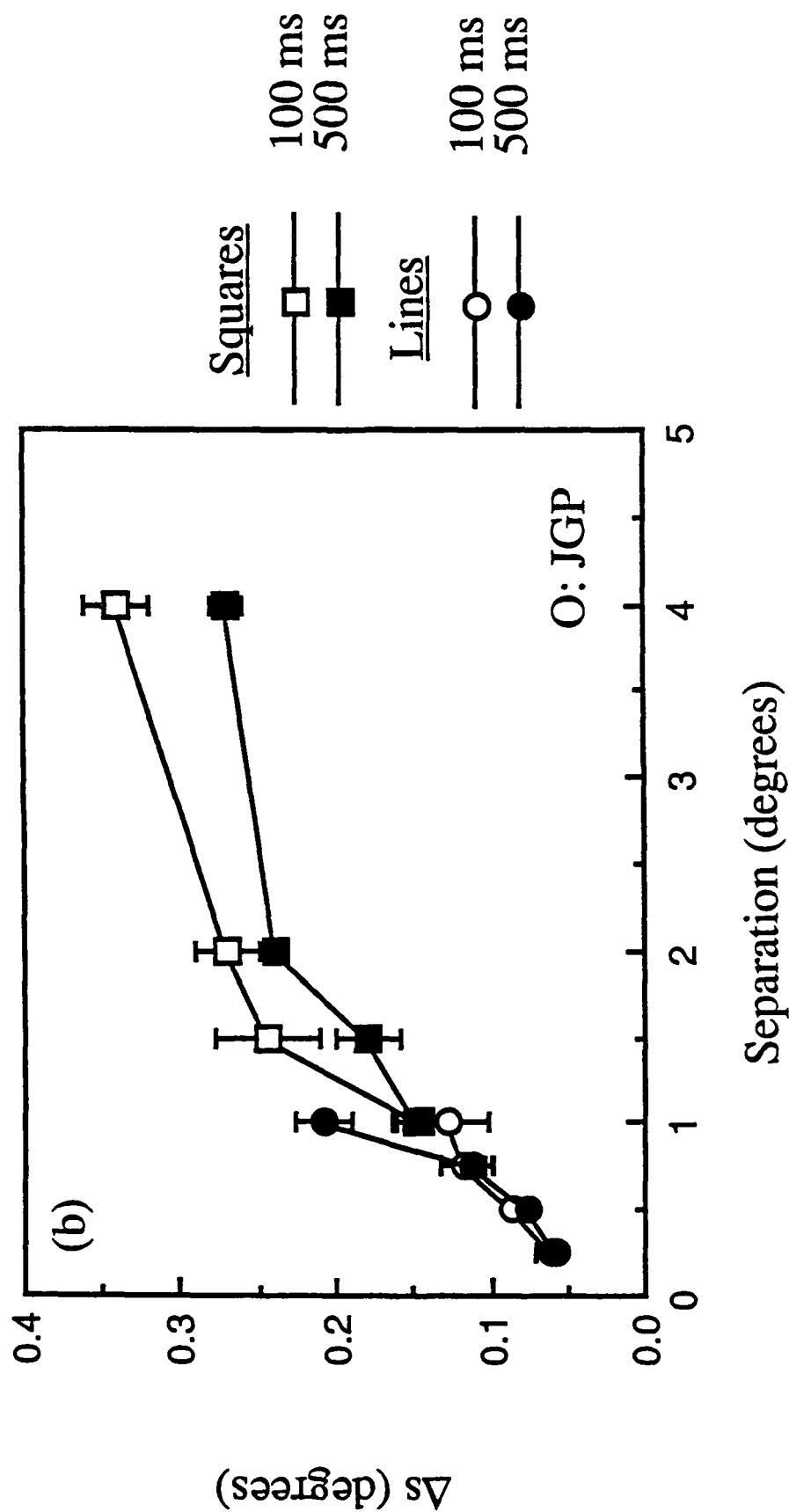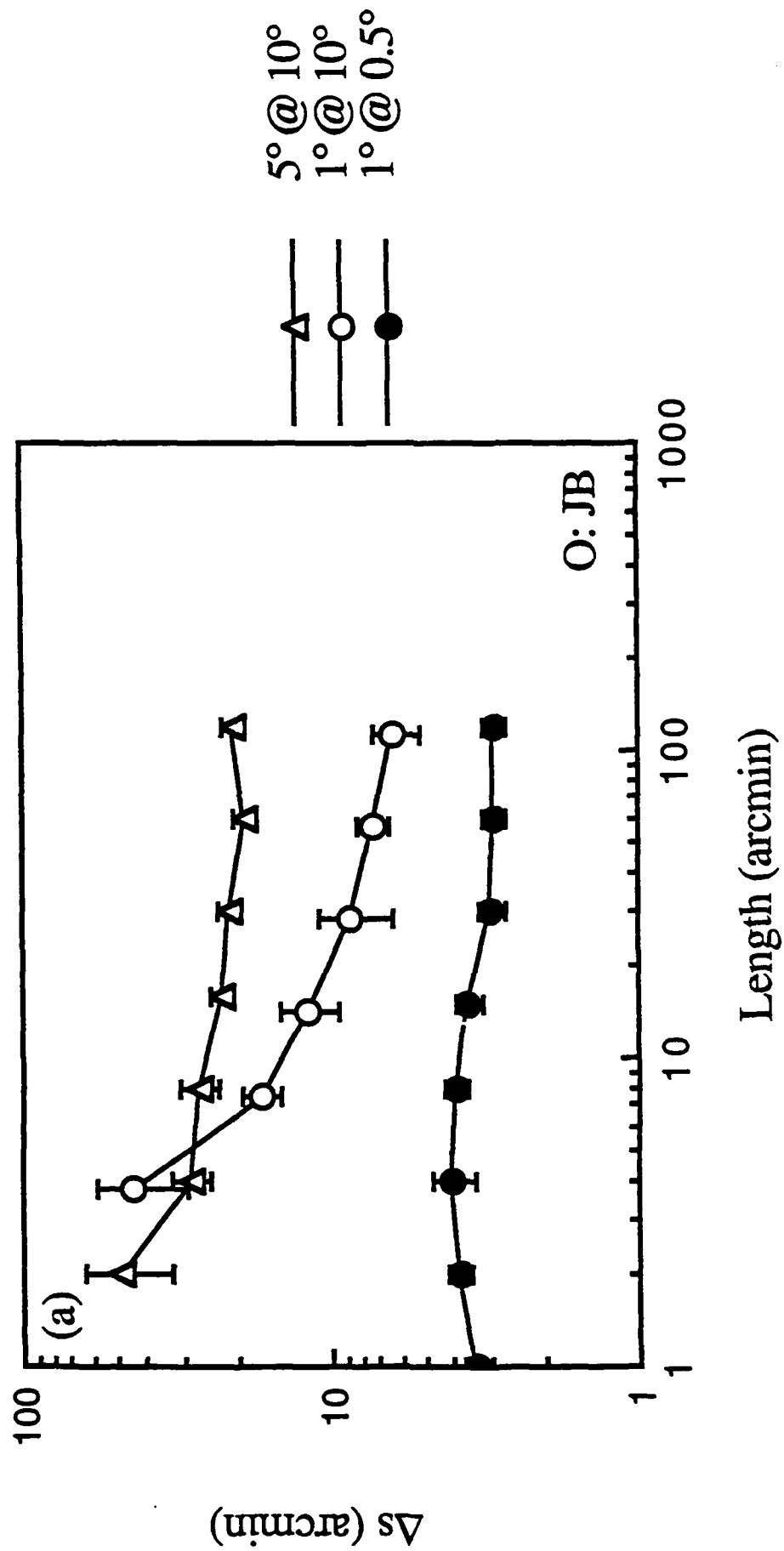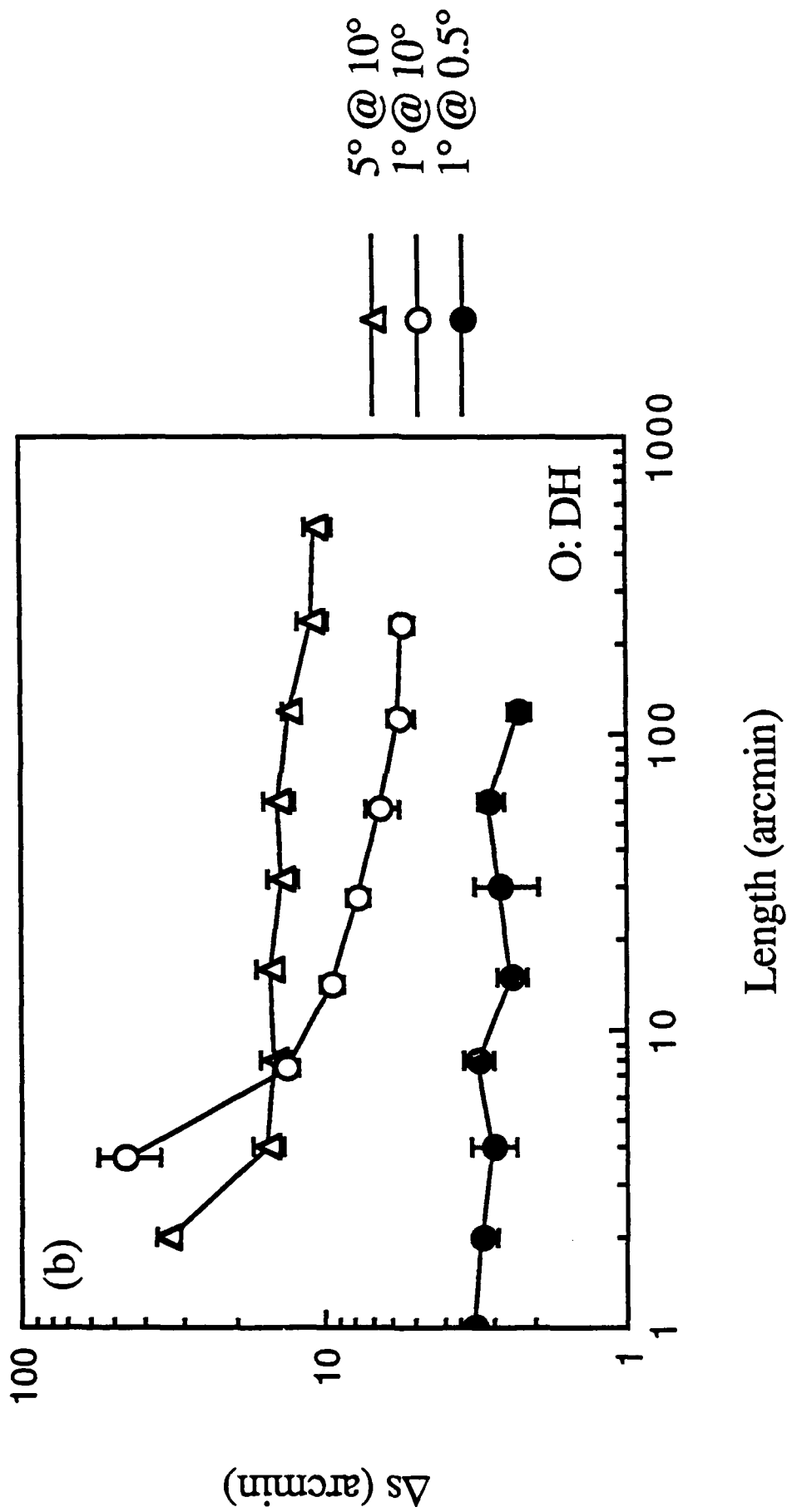Christina A. Burbeck and Yen Lee Yap
"Two Mechanisms for Localization?"
Fig. 8b

Appendix B

SPATIAL FILTER SELECTION IN LARGE-SCALE SPATIAL INTERVAL DISCRIMINATION

Christina A. Burbeck and Yen Lee Yap

Spatial-Filter Selection in Large-Scale Spatial-Interval Discrimination

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Spatial-interval discrimination thresholds were measured for a pair of bars in the presence of other parallel bars placed far enough from the targets as to be outside the range of neural and optical blurring. Thresholds were elevated when the targets were embedded in an array of four parallel bars (two between and two flanking the targets), but not when there were only two parallels, whether the parallels were between the target bars or flanking them. The threshold elevation was larger with a 100-ms than with a 500-ms exposure duration. Attenuating the high spatial frequencies magnified the threshold elevation. The data indicate that the process responsible for spatial-interval discrimination automatically selects which spatial filters to use; it does not have to scan through all ranges of spatial filters.

INTRODUCTION

Much research on spatial-interval discrimination has focused on attempts to explain the phenomenon in terms of the responses of individual local spatial filters, such as those postulated by Wilson and Bergen (1979) or Watson (1982). The idea has been that the spatial filters themselves carry the information about the size of the spatial interval. In those models, large intervals are indicated by activity at low spatial frequencies, small intervals by activity at high spatial frequencies, and so forth. However, several studies have shown that manipulating the spatial frequency content of the stimulus has no effect on the interval judgment (Morgan and Ward, 1985; Toet, van Ekhout, Simons and Koenderink, 1987; Burbeck, 1987, 1988). For example, accuracy is as high for a pair of high-spatial-frequency targets as for a pair of low-spatial-frequency targets, even when the separation between the targets is so large that the high-spatial-frequency targets could not possibly be detected by the same spatial filter (Toet et al., 1987; Burbeck, 1987). Spatial-interval discrimination thresholds are also unaffected if one of the targets stimulates only high- and the other only low-spatial-frequency filters (Burbeck, 1988).

Collectively, these data suggest that the local spatial filters provide information about the positions of individual targets rather than about the separation between the targets. The critical problems thus are to discover the relationship between the spatial filters and separation or size judgments and, ultimately, to discover the nature of the process responsible for such judgments. The research reported here focuses on how information from local spatial filters is used in separation judgments.

Most of the experiments in the studies mentioned above used targets presented on uniform backgrounds. For such stimuli, any spatial filters whose responses vary significantly between trials could provide useful information; there is no need for the system to select among filters. Thus, these experiments leave open the question of whether the size processor is able to select which filters to use, or whether it responds automatically to any stimulation present.

Addressing similar questions, Morgan and Ward (1985) studied the effects of parallel flanking lines on spatial-interval discrimination for lines separated by a few (3, 6, or 12) arc min. They found no effects for flanking lines sufficiently far from the targets to eliminate optical or neural blur, and conclude that the spatial filters responsible must be extremely small (too small to detect both the targets and the flanking lines simultaneously). However, Morgan and Ward do not provide compelling evidence that larger filters are employed in the absence of flanking lines, nor do they provide a rule for changing between filter sizes. Thus, it is still not clear whether the size processor can choose the best filter and, if it can, which filters it uses under which circumstances.

Watt (1987) has suggested that scale selection is automatic. Specifically, he suggests that although information is initially available at all scales, the visual system obtains its geometric information from the coarsest available filter. As time progresses, the larger spatial filter responses are switched off, leaving progressively smaller filters to convey geometric information. This model accounts for the effects of exposure duration on several spatial tasks, under the assumption that larger spatial filters provide poorer positional information. However, direct tests of that assumption find no such relationship (Toet et.al, 1987; Burbeck, 1987, 1988)).

The present study addresses the problem of scale-selection by examining jointly the effects of flanking lines and exposure duration. In this study a large separation is used to increase the range of spatial frequencies that carry pertinent information, thereby making it easier to determine whether the addition of parallel lines changes the range of spatial frequencies used in the discrimination task. The basic hypothesis being tested is as follows. We assume that larger spatial

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filters have higher signal to noise ratios than smaller spatial filters, on the basis of standard contrast sensitivity results. When the targets are presented on a uniform background, we hypothesize that the size processor uses the filter with the highest signal-to-noise ratio i.e, the largest spatial filter or lowest-spatial-frequency filter, that can detect one target without detecting the other. When there are lines flanking the targets, the large spatial filters respond to the flanking lines as well, and so yield unreliable information about the position of the target. In this case, a smaller filter, i.e., one tuned to a higher spatial frequency, will be used. Information from this filter is better in this case because it has a smaller receptive field size, and thus detects the targets without interference from the flanking lines.

We test this hypothesis by determining which spatial frequency ranges are carrying the relevant information with and without flanking lines. This determination is made by adding a diffusion screen to attenuate middle and high spatial frequencies in the stimulus and by varying the exposure duration, from 100 to 500 ms. Attenuating middle and high spatial frequencies by a diffusion screen shows directly the role those frequency ranges play in the determination of threshold. The exposure duration effect is more subtle. It has been shown previously that, for durations longer than about 100 ms, the effect of exposure duration on spatial-interval discrimination thresholds depends on which spatial-frequency range is carrying the relevant information (Burbeck, 1986). The effect is larger when the relevant spatial frequency range is high, regardless of the interval size. With the large intervals and bar targets used in the experiments reported here, exposure duration has at most a small effect when the targets are presented on a uniform field. If the addition of flanking lines causes the exposure duration effect to increase, it suggests that higher spatial frequencies are being used in the presence of the parallel lines than were used in their absence.

METHODS

Spatial-interval discrimination thresholds were measured using the method of constant stimuli. On each trial, a single pair of bars was presented and the observer was asked to report whether the separation between the bars was larger or smaller than the average separation seen on previous trials. The target separations (measured center to center) ranged from 2.77° to 3.07°. The average separation was 2.92°.

Our stimuli were displayed on a high-resolution monitor, which was controlled by a microcomputer. Details of this display are given elsewhere (Burbeck, 1986). The target and parallel bars each subtended 11.3° horizontally and 0.34° vertically. They were presented at 45% (Michelson) contrast on a 90 cd/m^2 background that measured 29 cm by 39.4 cm, or 10.6° vertically by 14.4° horizontally at the 155-cm viewing distance used. The position of the entire stimulus was varied randomly from trial to trial relative to the upper and lower edges of the display (within the range ± 19.3 arcmin relative to the centered position) to prevent the edges of the display from providing useful position cues. The room was dark. Viewing was monocular, unless indicated otherwise. The exposure duration of the target and parallel bars was a parameter of the individual experiments.

The exact distance of each parallel from the nearest target was chosen randomly from trial to trial from the range 46 to 72 arcmin (center-to-center). A range of distances to the parallels was used so that the distance between the parallels themselves (in particular, between the inner parallels) could not be used to gain information about the target separation. The range that was used allows the bars to be clearly resolved. This range also places the parallels outside the range of neural crowding, as indicated by data on the effects of flanking lines on vernier acuity (Levi, Klein and Aitsebaomo, 1985) and on bisection (Yap, Levi and Klein, 1987). Both studies found that for

retinal eccentricities less than about 2.5°, flanking lines have no effect when the distance between the target and flanking line exceeds 25 arcmin. Because our target lines were seen at an average eccentricity of 1.46° (half of the 2.92° separation) and were always more than 25 arcmin (edge to edge) from the nearest target, any effects of our parallels must be attributed to a mechanism other than the lateral interactions that affect vernier acuity and bisection thresholds.

The stimuli were presented with abrupt temporal onsets and terminations. Several exposure durations were used: 102 ms, 255 ms, 510 ms, and a condition in which the stimulus was presented continuously until the observer responded (response-terminated condition).

Data were collected in sessions of 84, 154, or 294 trials (depending on the endurance of the observer); the first 14 trials in each session (which constituted the first block of stimuli) were for practice and were not included in the data analysis. At least 210 nonpractice trials were conducted for each condition and each observer. Threshold estimates from each session were determined at the 84% correct level by standard probit analysis techniques (Finney, 1971). For data collected from more than a single session, the geometric mean of individual threshold estimates was calculated with each individual threshold estimate weighed by its inverse variance. The between-session variability was incorporated into the stardard error by multiplying the conventional standard error by the reduced X^2 (= X^2/degrees of freedom) for a reduced $X^2 > 1$. This method takes into account the goodness of fit of the geometric mean to the individual threshold estimates (Bevington, 1969).

A total of five observers was used. All had normal or corrected-to-normal vision.

RESULTS

Embedding the Targets in an Array of Four Parallel Bars

In these experiments, spatial-interval discrimination thresholds were measured with the target bars embedded in an array of four parallel bars, as shown in Fig. 1a. Spatial-interval discrimination thresholds were also measured using just the target bars, with no extraneous parallels. These control data were obtained under the same experimental conditions in sessions interleaved with the four-parallels data sessions.

Considering the stimuli in terms of their Fourier spectra, addition of the parallel bars adds energy at a broad range of spatial frequencies (because the bars are broad-band targets). The outside parallels add most energy at a frequency slightly lower than the separation frequency (the reciprocal of the target separation). The inside parallels add most energy at frequencies higher than the separation frequency. However, if we assume that the receptive field size of the local spatial filters decreases with increasing spatial frequency, then the smaller receptive fields of middle- and high-spatial-frequency filters give them an advantage not evident in the Fourier spectra: namely, if its receptive field size is sufficiently small, a local spatial filter could detect a target while being unaffected by the parallel bars. Thus, if the size processor can select the best filter, then it should select a middle or high-spatial-frequency filter when the targets are embedded in four parallel bars, and it should select a lower-spatial-frequency filter when the targets are not flanked by other bars, under the assumption that a lower-spatial-frequency filter has a lower signal-to-noise ratio. The particular frequency range that would be best in each case would depend on the exact sensitivities and bandwidths of the local spatial filters as well as on the stimulus characteristics.

If the size processor does choose the best filter for the four-parallels condition, then at short exposure durations, thresholds may be elevated relative to the no-parallels condition (because

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thresholds based on the responses of high-spatial-frequency filters are elevated at short exposure durations). At longer exposure durations, however, the threshold with parallels should return approximately to the value obtained with no parallel bars. Previous research has shown that, for long exposure durations, spatial-interval discrimination thresholds are roughly equal whether based on low- or high-spatial-frequency information (Burbeck, 1986). However, the addition of parallel bars would be expected to add to the overall noise of the system. Thus, the key issue here is not whether the parallel bars elevate thresholds at all, but whether the effect of exposure duration is accentuated by the addition of the parallels. Most models based on the responses of single filters would predict an overall change in sensitivity; thus any arguments based on such a result would have to be quantitative, and therefore critically model dependent. However, most models would not predict a change in the effect of exposure duration, and any such change would therefore be highly informative.

Data for two subjects and a range of exposure durations are shown in Fig. 2 a and b. The data for the targets with no parallel bars show no effect of exposure duration, consistent with previous reports using large separations (Burbeck, 1986). However, when the targets are embedded in four parallel bars, the exposure duration effect becomes highly significant. Thresholds are substantially elevated at durations of 100 and 255 ms, and are elevated only slightly or not at all at the longest durations used. This is consistent with the hypothesis that the relevant spatial frequencies are shifted to a higher range by the addition of the parallel bars.

To test further the hypothesis that the visual system is using higher spatial frequencies to make the spatial-interval discrimination judgment when the targets are embedded in four parallel bars, we attenuated those higher spatial frequencies using a diffusion screen placed in front of the display monitor.

Spatial-Interval Discrimination with Middle and High Spatial Frequencies Attenuated

The spatial frequency characteristic of the diffusion screen was calibrated by measuring contrast sensitivities for horizontal sine-wave gratings with and without the screen in place. Contrast thresholds were measured using a standard yes/no staircase procedure. Eight pairs of contrast reversals from two interleaved staircases were averaged to yield an estimate of contrast threshold. The horizontal gratings subtended 12.4° x 9.1° and were presented for 100 ms. Other experimental conditions were the same as for the other experiments.

The ratios of the contrast thresholds obtained with and without the diffusion screen in place are plotted in Fig. 3. Contrast is rapidly attenuated with increasing spatial frequency. Thus if higher spatial frquencies are involved in the four-parallels case than in the no-parallels case, then the diffusion screen should have a more pronounced effect with four parallels present than with none.

Spatial-interval discrimination thresholds were measured with and without the diffusion screen in place. The ratios of these thresholds, which are a measure of the effect of the diffusion screen itself, are shown in Fig. 4. In the no-parallels case, the diffusion screen had a small significant effect. In the four-parallels case, there was a large significant effect whose magnitude depended on exposure duration. Although these data look like those shown previously (Fig. 2), in fact they tell quite a different story. Specifically they show that attenuating the high spatial frequencies had a larger effect with a 100-ms than with a 500-ms duration. This implies that high-spatial-frequency filters play an important role in determining the 100-ms threshold. This finding is not consistent with a coarse-to-fine analysis of the visual scene, as proposed by Watt (1987). This issue will be considered further in the disucssion.

The data of Fig. 4 indicate that lower spatial frequencies are used when parallels are absent than when they are present. In short, when the low-spatial-frequency filters do not provide good information, higher-spatial-frequency filters are used.

Does the size processor always use high spatial frequencies in the presence of parallels or can it employ a strategy of using the best available information? To answer this question, we measured spatial-interval discrimination thresholds with just two parallel bars. These parallels either flanked the target pair, as shown in Fig. 1b, or lay between the targets, as shown in Fig. 1c. If the receptive fields used in these cases are the same as those used in the four parallels case, then the exposure duration effect should remain the same. On the other hand, if the relevant receptive fields are tuned to local spatial filters in the low- to medium-spatial-frequency range, then thresholds should not be substantially affected relative to the no-parallels case.

Spatial-Interval Discrimination with Outside Parallel Bars

This experiment was identical to the initial experiment reported above except that the bars between the targets were removed, as shown in Fig. 1b. It is similar to an experiment performed by Morgan and Ward (1985) using small separations.

Two exposure durations were tested, 100 and 500 ms. Data for two observers are shown in Fig. 5. Also shown for comparison are data obtained with no parallels. (The inside-parallels condition, which is also shown in this figure, will be discussed below.) At the short exposure duration, the outside parallels elevated thresholds significantly. However, informal observation suggested that the outside bars appeared to create a reference frame that affected the perceived depth of the targets. As that reference frame changed from trial to trial, the perceived depth of the target bars changed, and with that change in perceived depth seemed to come a change in perceived separation.

To test the validity of these observations, spatial-interval discrimination thresholds were remeasured with binocular viewing and dim room illumination to facilitate acquisition of depth information. If the outside parallels were affecting threshold by affecting perceived depth, then these changes would reduce or even eliminate the effect. Data were collected from two new observers for 100-ms duration, with monocular and binocular viewing in interleaved sessions. Data for the no-parallels and four-parallels conditions with both monocular and binocular viewing were also collected in interleaved sessions for comparison.

The data for the outside-parallels condition are shown in Fig. 6a and for the four-parallels condition, in Fig. 6b. Data are shown for two observers. The data obtained with monocular viewing replicate the effects reported above. One observer had a large effect, the other a small but significant one. [Large differences between observers in overall sensitivity are frequently obtained in separation discrimination experiments (Morgan and Regan, 1987; Yap, Levi and Klein 1989; Levi and Westheimer, 1987).] With binocular viewing, neither observer showed a significant effect of the outside parallels (Fig. 6a). For Observer CAB, the ratio of the outside-parallels threshold to the no-parallels threshold was 1.4 ± 0.2 for monocular viewing and 1.0 ± 0.1 for binocular viewing. For Observer MAC, the same ratio was 1.3 ± 0.2 for monocular and 1.1 ± 0.2 for binocular viewing. The absence of a significant effect of the outside parallels under binocular viewing conditions confirms the observation that the outside parallels affected the perceived depth of the target bars when viewing was monocular. Apart from this depth effect, the outside parallels had no effect on the separation discrimination threshold, suggesting that low-spatial-frequency filters can be used in the presence of parallels.

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The change in viewing conditions did not have the same effect on thresholds for the four-parallels condition (Fig. 6b). For Observer CAB, the ratio was 2.2 ± 0.5 for monocular viewing and 2.3 ± 0.5 for binocular viewing. For Observer MAC, the monocular ratio was 1.5 ± 0.2 and the binocular ratio 1.5 ± 0.2. Thus, the effect of four parallels cannot readily be attributed to trial-to-trial changes in the perceived depth of the stimulus. The original hypothesis—that embedding the targets in four parallels changes the relevant range of spatial frequencies—is not contradicted.

Spatial-Interval Discrimination with Parallel Bars Between the Targets

Spatial-interval discrimination thresholds were measured in the presence of parallel bars lying between the target pair, as shown in Fig. 1c. All other experimental conditions were the same as in the previous experiments. Thresholds were measured for exposure durations of 100 and 500 ms.

Figure 5 shows data for two observers. For one observer, there was a small threshold elevation in the presence of the inside parallels that did not vary with exposure duration. For the other, there was a small significant decrease in threshold at the 500-ms exposure. Overall, the addition of bars between the targets had little effect, supporting our previous conclusion that low-spatial-frequency filters can be used in the presence of parallels. However, this result is not compatible with the idea that the separation itself is encoded in the response of a low-spatial-frequency filter, and we conclude that the separation is encoded at a higher level of processing than that at which local spatial filtering occurs. Given the large separation involved, that conclusion is not surprising.

We can readily explain why embedding the targets in four parallels has a substantial effect that varies with exposure duration, whereas presenting the targets with only two parallels does not. We begin by assuming that different local spatial filters are providing information about the target positions in each case. We further assume that within each filter size, the filters with the largest responses are used. These filters provide the highest signal-to-noise ratio, though not the highest sensitivity to local position. Previous research on large-separation discrimination indicates that contrast is a more important variable in this task than is local positional resolution. Increasing the contrast, up to about five times threshold, decreases the threshold significantly; enhancing the high-spatial-frequency content of the targets does not (Burbeck, 1987). The argument proceeds as follows: When each target bar is crowded on only one side, as they are in the two-parallels conditions, they can be detected by filters of relatively low spatial frequency that are not centered on the targets. In this case, an odd-symmetric, low-spatial-frequency filter, such as an edge detector, could respond well to one of the targets and yet be unaffected by the outside parallels (although it would be strongly affected by an inside parallel). Similarly, another odd-symmetric filter could respond well to one of the targets but be unaffected by the parallels between the target pair (although it would be strongly affected by an outside parallel). When the targets are embedded in four parallels, however, such filters would be stimulated by the parallels as well as by the targets and thus would be too noisy to be useful; smaller, even-symmetric filters, such as line detectors, would be most useful in this case.

As another means of testing whether low-spatial-frequency filters are used in the two-parallels conditions, we measured separately the effect of the diffusion screen on thresholds measured with inside parallels and with outside parallels. The results are shown in Fig. 7. (One of the observers whose data are shown in Fig. 5 was not available for retesting.) Use of the diffusion screen does not have a significantly different effect in the two-parallels conditions from its effect in the no-parallels condition, although there is a suggestion of a slightly larger effect for the inside parallels than for the outside and no-parallels conditions. These data indicate that

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higher-spatial-frequency filters are involved in the four-parallels case than in the two-parallels cases. They also suggest that the same range of spatial filters may be responsible for the no-parallels and the two-parallels conditions.

DISCUSSION

The experiments reported here show that spatial-interval discrimination thresholds depend on the context within which the targets are placed. When the targets are embedded in an array of four parallel lines, the low spatial frequencies of the stimulus array no longer carry the most accurate information about the positions of the individual targets. Under those conditions, spatial-interval discrimination thresholds are elevated, particularly at short exposure durations. This exposure duration effect together with the threshold elevation that results when the middle and high spatial frequencies are attenuated by a diffusion screen, indicates that, under these conditions, spatial-interval discrimination is being done on the basis of middle- or high-spatial-frequency information, which, according to current models, is obtained more locally than is low-spatial-frequency information. Thus, under cluttered conditions, units with smaller receptive fields appear to be used.

What are the rules governing this selection? Watt (1987) proposed that the frequency range of spatial filters in operation shrinks after stimulus presentation: initially the low-spatial-frequency filters provide information about the geometry of the stimulus and as time advances, the lower-spatial-frequency filters are switched out, leaving only the higher spatial-frequency filters to convey the information. (To account for data from a spatial resolution experiment, Watt theorizes that nongeometric information is always available at the finest scale, but such information is not important in our experiments.) Can Watt's model account for our data? It appears to be compatible with our finding that in the four-parallels condition, accuracy improves over time. However, such improvement is also predicted by a theory in which high-spatial-frequency filters with long temporal integration times are always providing the information for this task (as postulated previously to account for the exposure duration effects seen in separation discrimination tasks involving small separations or large separations between high-spatial-frequency targets (Burbeck, 1986).] The experiments conducted with the diffusion screen can discriminate between these two theories. If low-spatial-frequency filters are providing the information about the separation in the four-parallels and 100 ms duration case, and the high-spatial-frequency filters are providing the information when 500 ms duration is used, then interposing the diffusion screen should have a smaller effect with a 100 ms than with a 500 ms duration. On the other hand, if high-spatial-frequency filters are providing the relevant information in both cases, then the diffusion screen should elevate thresholds as much, or more, with 100 ms than with 500 ms duration. The data are conclusive. There is substantially greater threshold elevation with the 100 ms than with the 500 ms duration. This result is not consistent with a coarse-to-fine analysis, but is consistent with an *a priori* selection of the high-spatial-frequency filters as the preferred source of information for this task.

We propose that the rule for spatial scale selection is: Use the strongest signal that conveys the required information. If larger spatial filters have higher signal-to-noise ratios, then the rule is equivalent to: Use the largest spatial filter that conveys the relevant information. In the case of separation discrimination with targets embedded in four flanking lines, the strongest relevant signal always comes from relatively small filters. Although the larger filters have the strongest signal initially, they do not provide the best information for this task because they are stimulated by the flanking lines as well as by the targets. When the targets are presented in an uncluttered field, the strongest relevant signal comes from larger spatial filters. If the observer has no prior knowledge of the stimulus or task, it may be that he will scan the filters from a coarse to a fine scale because

the coarser filters often give the strongest response, especially initially. There is no data that we know of that is conclusive on this point.

There is some neurophysiological support for selection of the type we propose. In studies of the effects of attention, Desimone and colleagues have found that if a monkey restricts his attention to one location within the receptive field of a neuron in area V4 (fourth visual area) or IT (inferotemporal cortex), "the response of the cell is determined primarily by the stimulus at the attended location, almost as if the receptive field 'shrinks' around the attended stimulus" (Wise and Desimone, 1988; Moran and Desimone, 1985). This spatial shrinkage could correspond to the transition from large, low-spatial-frequency filters to smaller, high-spatial-frequency filters that was evident in our study.

In sum, we have found that size judgments can be made on the basis of information from different spatial-frequency ranges under different experimental conditions. For widely separated target bars in an uncluttered field, lower spatial frequencies are used, but when the target bars appear in a cluttered field, higher spatial frequencies are sometimes used. These results add to the growing body of data indicating that information about the spatial interval is not carried directly in the responses of spatial filters, but that subsequent processing is required to extract the separation information.

In 1979, Westheimer eloquently argued that our sense of object position as "immediate, primary—not further reducible" should serve as a starting point for doing science in this area. Opposing this view were frequency-channel theorists who pooled all spatial properties in the responses of local spatial filters. Ten years later we appear to be returning to the idea that there is a specific process dedicated to determining the relative positions of objects or features. Spatial filters are still included in the discussion, but they are now components of a more complex process and not ends in themselves.
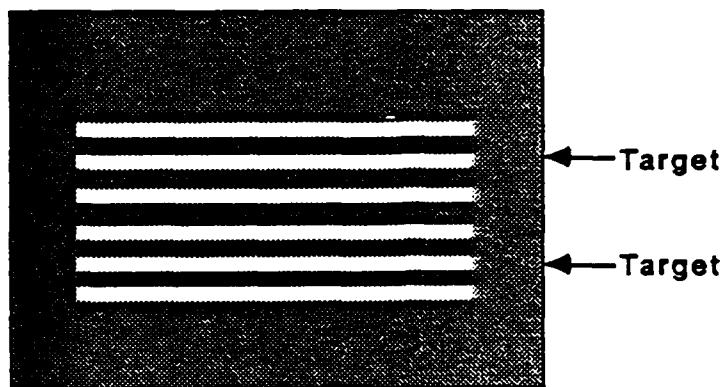
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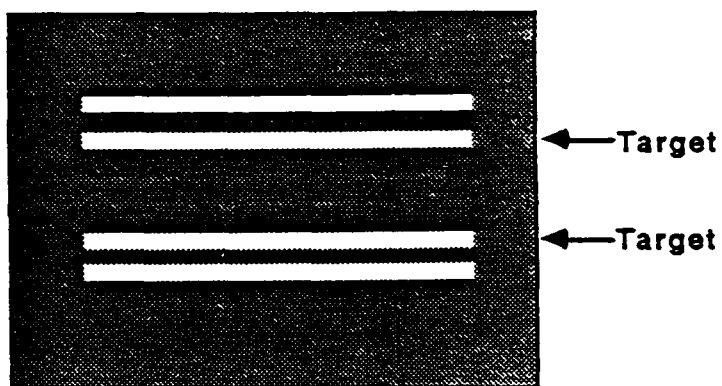
Figure Captions

Fig. 1 Three of the stimulus configurations used. The distance between the targets was the independent variable in the experiment. The distance between each parallel and the nearest target was randomly changed from trial to trial and was determined separately for each parallel, so that, in general, the bars were not equally spaced.

Fig. 2 Separation discrimination thresholds for a pair of bars embedded in an array of four parallel bars at four exposure durations: 102 ms, 255 ms, 510 ms, and response-terminated. Also shown are data obtained without parallels. Data are shown for two observers.

Fig. 3 Diffusion screen calibration. The contrast threshold ratios were calculated by dividing the contrast thresholds obtained without the diffusion screen by the contrast thresholds obtained with the diffusion screen in place.

Fig. 4 Effects of the diffusion screen on separation discrimination thresholds measured with four parallel bars and with no parallel bars. The threshold elevation ratio was obtained by dividing the threshold obtained with the screen present by the threshold *for the same stimulus condition* obtained without the diffusion screen. Thus, this ratio indicates the effect of the diffusion screen only.

Fig. 5 Effects of two extra parallel bars on separation discrimination thresholds. Data are shown for two observers and two exposure durations. "Outside parallels" is the stimulus condition shown in Fig. 1b. "Inside parallels" is the stimulus condition shown in Fig. 1c. "No parallels" is the standard two-bar separation discrimination stimulus.

Fig. 6 Separation discrimination thresholds obtained under monocular and binocular viewing conditions. a) Outside-parallels condition (squares) and no-parallels condition (circles). b) Four-parallels condition (squares) and no-parallels condition (circles). Data are shown for two observers. O:MAC, filled symbols. O:CAB, open symbols.

Fig. 7 Effects of the diffusion screen on separation discrimination thresholds obtained with outside parallels (Fig. 1b) or inside parallels (Fig. 1c). Also shown for comparison are the data from Fig. 5 obtained with four parallels and with no parallels.

Figure 1

a) Targets Embedded in
Four Parallel Bars

←—Target

←—Target

b) Targets with Parallel Bars
Outside

←—Target

←—Target

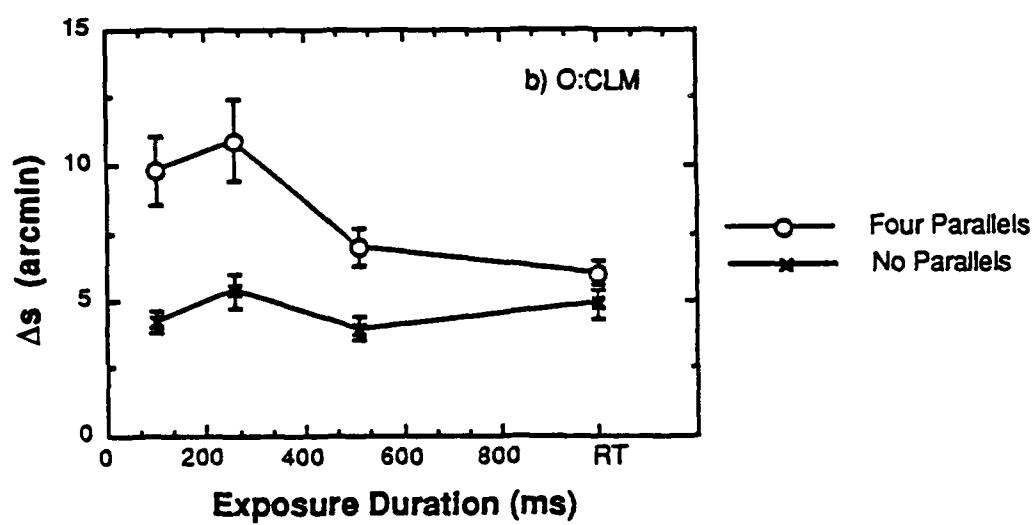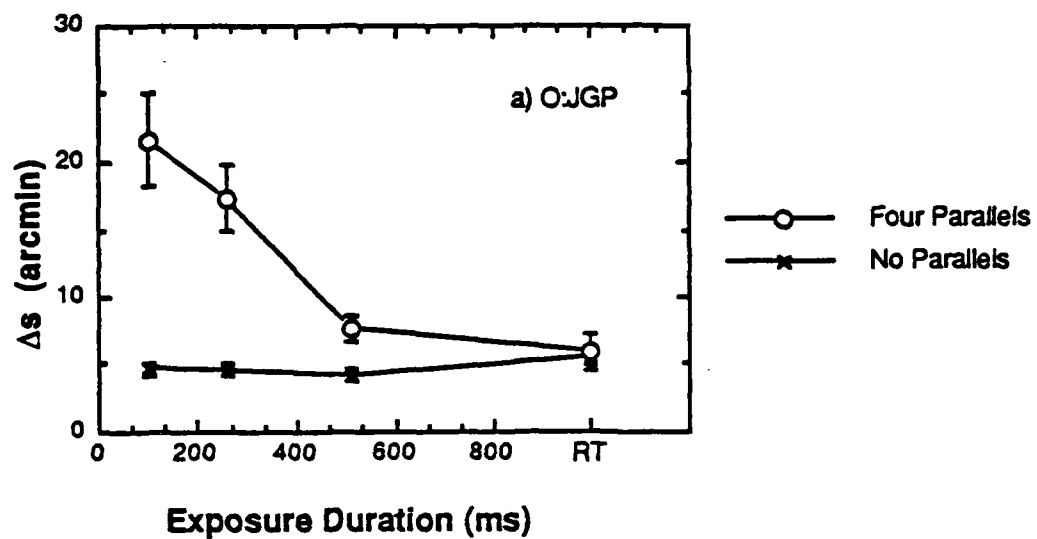c) Targets with Parallel Bars
Inside

←—Target

←—Target

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Figure 2

Figure 3

Spatial Frequency (cycles/degree)

Figure 4

Figure 5

a) O:JGP

b) O:JGG

Figure 6

a)

b)

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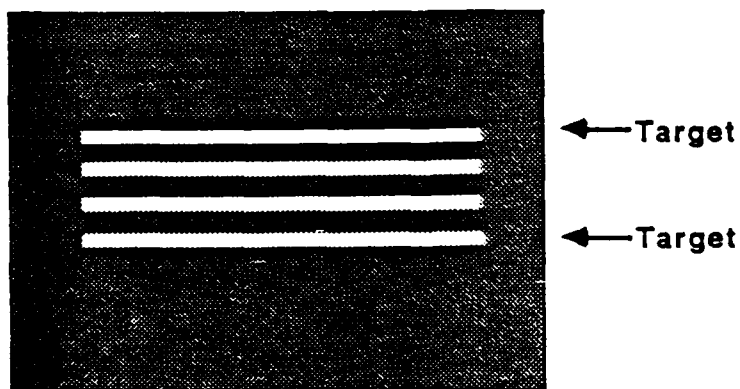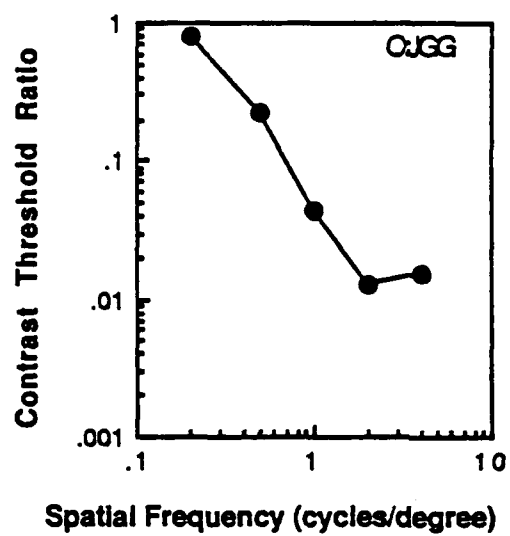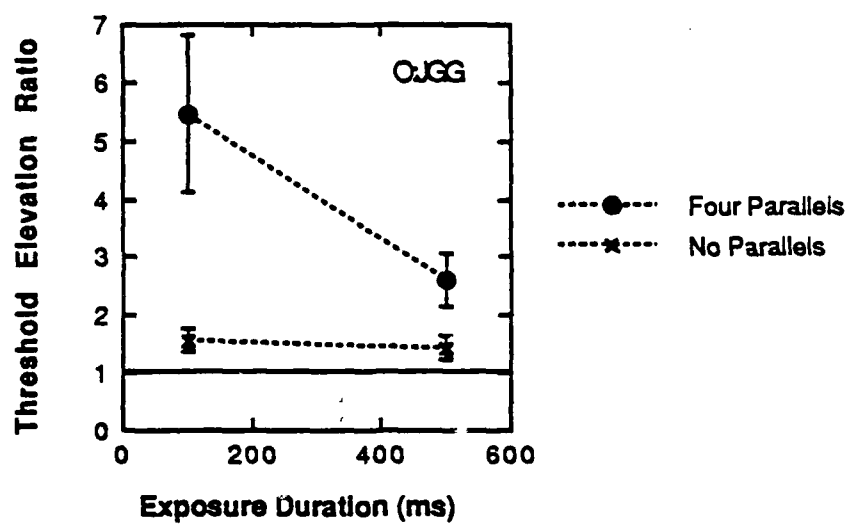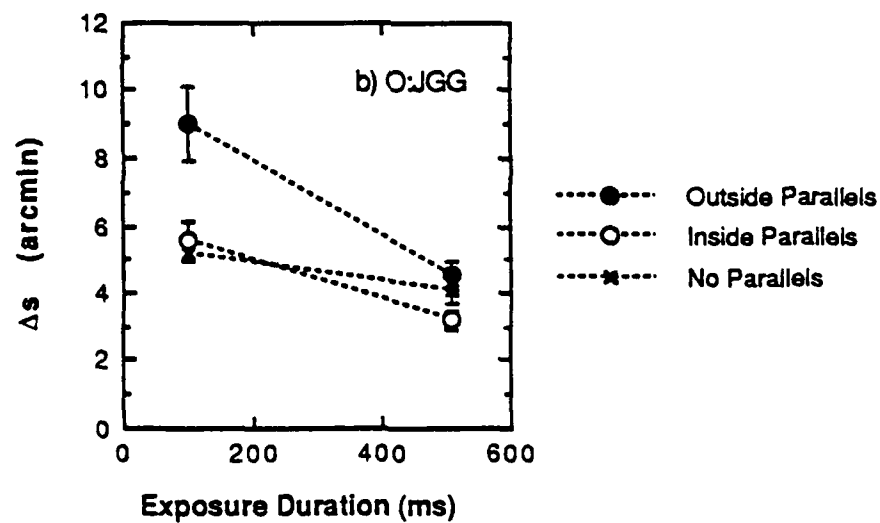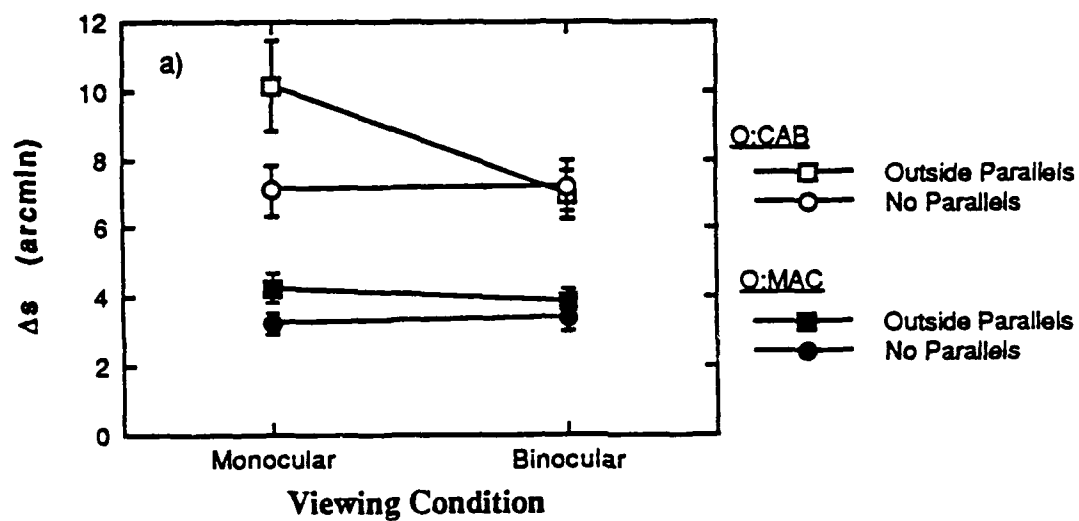
Figure 7

Figure 7
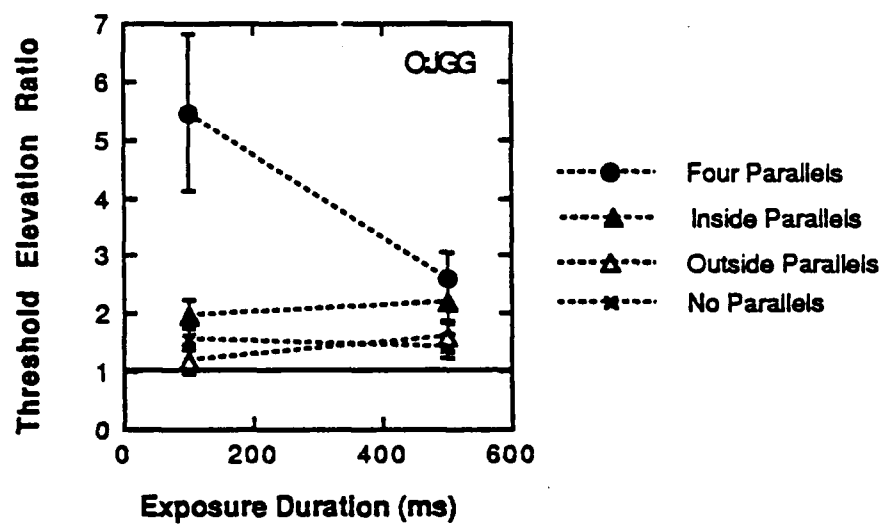
Appendix C

SPATIOTEMPORAL LIMITATIONS IN BISECTION AND SEPARATION DISCRIMINATION

Christina A. Burbeck and Yen Lee Yap

SPATIOTEMPORAL LIMITATIONS IN BISECTION AND SEPARATION DISCRIMINATION

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Exposure duration is found to have a different effect on bisection thresholds than on separation-discrimination thresholds. Bisection thresholds dec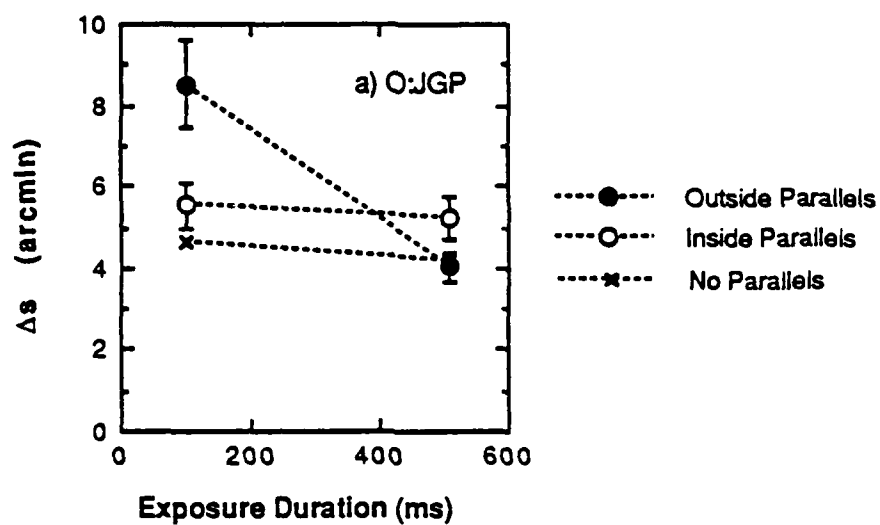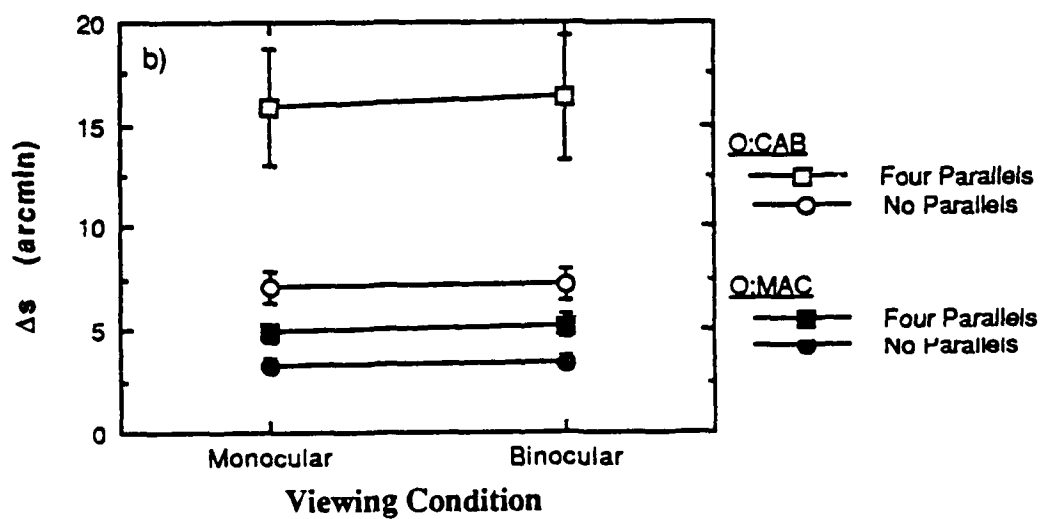rease more between 33 and 150 ms than do separation-discrimination thresholds. Experiments in which stimulus contrast is manipulated show that the effect of exposure duration on separation-discrimination and bisection thresholds cannot be attributed to temporal contrast integration. The data can be accounted for by a model in which bisection is done by encoding the two separations in bisection sequentially.

INTRODUCTION

For more than 100 years, scientists have been interested in how the human visual system encodes inter-object distances. In the 1860's, Fechner and Volkmann (as cited by Helmholtz, 1910) investigated the problem in their quest to understand the domain of applicability of Weber's law , but little progress was made in understanding the underlying processes. In the 1970's, Westheimer rekindled interest in the subject through his research on hyperacuity (e.g., Westheimer, 1975) and his recognition that position is a basic, irreducible, visual property of objects (Westheimer, 1979).

A means of encoding information about the relative positions of objects was suggested by the discovery of size- or frequency-tuned mechanisms in human vision. Indeed, such mechanisms have proven to be helpful in accounting for some properties of separation-discrimination thresholds (Wilson and Gelb, 1984; Klein and Levi, 1985; Burbeck, 1986; Levi, Klein and Yap, 1988; Toet, Snippe and Koenderink, 1988; Yap, Levi and Klein, 1989). However, as recent experimental work shows (Morgan and Ward, 1985; Burbeck, 1987; Toet and Koenderink, 1988; Burbeck and Yap, in press), these mechanisms are unable, by themselves, to account for the entire phenomenon.

More plausible than simple channel models is a two-stage model (Watt and Morgan, 1985; Burbeck and Yap, in press; Hess, Pointer and Watt, 1989) in which some type of local spatial filtering occurs first and estimates of inter-object separation judgments are made at a subsequent stage of processing which, for

brevity, we refer to as the *separation discriminator*. Results of other experiments lend credence to the idea of a visual mechanism dedicated to encoding information about the relative locations of objects. In the research reported here, we investigate some of the temporal limitations of this theoretical separation discriminator.

The properties of the separation discriminator that have been uncovered so far suggest that it is quite a different type of mechanism than those postulated to account for contrast-detection thresholds. For example, whereas the size or spatial frequency of the target is a key parameter controlling contrast-detection thresholds (e.g., Robson, 1966), it is of little importance in separation-discrimination tasks. Separation-discrimination thresholds are largely independent of the size or spatial-frequency content of the individual targets, provided the signal strength is adequate (Burbeck, 1987, 1988; Toet and Koenderink, 1988). Simlarly, contrast-detection thresholds vary markedly with retinal eccentricity (Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978; Rovamo, Virsu, and Nasanen, 1978), whereas, for a large range of separations, separation-discrimination thresholds vary only slightly (Toet et al., 1988; Yap et al., 1989). Thus, contrast detection and separation discrimination exhibit some fundamentally different dependences. This suggests that to understand the nature of the separation discriminator, we need to ask different questions than we do when studying contrast detection.

In the present study, we examine the temporal limitations of the separation discriminator. Specifically, we look at spatio-

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temporal interaction within the separation discriminator, asking the question: Are separation judgments performed simultaneously across the visual field [as was assumed when spatial filters were postulated to account for separation-discrimination thresholds], or does the separation discriminator operate sequentially on the various distances to be judged? Subjectively, it seems that separations are processed sequentially. However, using a field of many objects, Sagi and Julesz (1985) found that "where" target objects are is determined in parallel across the visual field, whereas "what" they are may be determined sequentially. It is not clear how their task relates to standard separation-discrimination tasks, however, so the answer is not yet fully known. The experiments reported here investigate the temporal limitations of the separation discriminator using standard separation-discrimination and bisection tasks.

EXPOSURE-DURATION EFFECTS IN BISECTION AND SEPARATION DISCRIMINATION

To measure the temporal characteristics of the processes underlying separation discrimination and bisection, we measured thresholds for both tasks using two separations and a range of exposure durations.

Methods

We measured separation-discrimination and bisection thresholds, using horizontal line stimuli, for two reference separations: 11 arcmin (11′) and 2.8 degrees (2.8°). For the small separation, the target lines subtended 16 x 2′; for the

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large separation, they subtended 32 x 4'. Viewing was monocular at a distance of 10.3 m and 1.0 m, for the small and large separation respectively, in an otherwise dark room. The stimuli were presented at 45% contrast on a 90 cd/m^2 gray background (Conrac 2400, 19 in. diagonal, 60-Hz noninterlaced frame rate, 512 x 512 pixels), where contrast is defined to be $(L_{max}-L_{min})/2L_{mean}$. The mask was presented at 90% contrast. Exposure durations for the test stimuli ranged from 33 ms to 500 ms.

The temporal and spatial configurations used in these experiments are shown schematically in Fig. 1. A trial began with a 500 ms presentation of a fixation line placed roughly in the middle of the display. This central fixation line subsequently served as one of the target lines. At the end of the fixation interval, the stimulus was displayed. In bisection, this meant that one line appeared above the center line and one appeared below, creating the standard three line bisection stimulus. In separation discrimination, displaying the stimulus meant that a line was shown above the center line, yielding the first separation to be judged. The second separation was shown in a second interval, as illustrated in Fig. 1. The second interval was the same as the first except that the stimulus consisted of the central line and a second line placed below the center line. Use of the central fixation line in both tasks ensured that the targets were presented in the same retinal locations for separation discrimination as for bisection.

Immediately following the stimulus presentation, a mask was presented for 500 ms. The mask consisted of three patches of square-wave grating, one patch covering each target location. For

the 11' separation, the patches were 15 c/deg gratings subtending 16' x 14'. For the 2.8° separation, they were 7.5 c/deg gratings subtending 32' x 144'. To prevent the observer from using the relative positions of the target and mask as a reference, the mask was displaced from trial to trial by a random vertical distance. For the small separation, the range of mask displacements was ±8' and for the large separation, ±80'. To prevent the observer from using distance to the top and bottom display edges as a cue, the overall vertical position of the stimulus on the display was varied randomly between presentations by ±2' to ±4' for the small separation and ±20' to ±40' for the large separation.

In each trial, one separation was the reference and the other was 1 to 7 steps larger or smaller than the reference. The size of the step depended on the separation and exposure duration used. The observer reported whether the upper or lower separation appeared larger. Right/wrong feedback was provided after every trial.

Each threshold point is based on at least 420 trials. Thresholds for individual sessions were calculated at the 84% correct level by standard probit analysis techniques (Finney, 1971). Threshold estimates from different sessions were combined by calculating the geometric means of the individual threshold estimates, weighted by their inverse variances. The error bars include both within- and between-session variability (Klein and Levi, 1987).

Three observers were used in these experiments. All had normal or correctable-to-normal vision. All were naive as to the purposes of the experiment.

Results

Figure 2 shows results of these experiments for all three observers and both separations. As expected, thresholds for the 2.8° separation were substantially higher than those for the 11' separation. For both separations, thresholds decrease markedly with increasing stimulus duration, particularly between 33 and about 150 ms. At longer durations, thresholds continued to decrease for the small separation, but for the large separation, the separation-discrimination thresholds appeared to flatten. This is consistent with the results of a previous separation-discrimination study in which the effect of exposure duration was studied in the 100 to 500 ms range (Burbeck, 1986).

The slope of the upper portion of the curves in Fig. 2 is similar for the two separations, averaging about -0.7 to -0.8 for the three observers. Thus, there is substantial integration of information about separation between 33 ms and 150 ms for both separations. There is not, however, the simple linear relationship between the two variables that would indicate perfect temporal integration.

The data in Fig. 2 exhibit another important, although more subtle, property. Exposure duration had a different effect on bisection thresholds than it had on separation discrimination thresholds. At short durations, separation-discrimination thresholds were consistently lower than bisection thresholds, whereas at long durations, bisection thresholds were lower than separation-discrimination thresholds. This pattern held for both the large and the small separation (except for observer JM at the

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small separation).

In classical terms, one would say that the temporal characteristics depend on the spatial properties of the stimulus, in short, that spatio-temporal interaction takes place. A more detailed analysis indicates the source of this interaction.

ANALYSIS OF THE EXPOSURE-DURATION EFFECTS: LOCAL SPATIAL FILTER MODEL

Our strategy for investigating the properties of the separation discriminator was to try first to account for the data in terms of the local spatial filters that constituted the first stage of spatial processing in our model. If the filters could not account for the data, then new attributes would be ascribed to the separation discriminator. These new attributes must, in turn, be checked by additional experimentation. In a previous study using this approach, Burbeck (1986) was able to account for the effects of exposure duration on separation-discrimination thresholds in terms of the properties of the local spatial filters, without having to ascribe any temporal integration to the separation discriminator. However, that study included only exposure durations greater than 100 ms. The data obtained with shorter durations exhibit quite different properties: the effects are larger and they are, at least to a first approximation, independent of target separation.

To keep our analysis as general as possible, we adopted a generic local-spatial-filter model with a range of filter sizes at each eccentricity, and with larger spatial filters having shorter

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integration times than smaller filters. If we assume that, for a given target separaation, bisection judgments are made on the basis of smaller filters than are separation-discrimination judgments, then bisection thresholds should increase with exposure duration over a longer time than do separation-discriminations. That was exactly what we found.

The assumption that bisection is based on smaller local spatial filters than is separation discrimination is not as implausible as it might first appear, at least for the small separation. In separation discrimination, the visual system could detect each target line with a relatively large, odd-symmetric filter, whose primary inhibitory lobe lay outside the target pair, without interference from the other line. In bisection, however, such filters would be useful only for the outer lines; they would not be useful for the center line because of interference by the outer lines. The largest local spatial filter that could detect the center line and not the outer lines would be smaller, and it would be even-symmetric.

Although this explanation of the interaction between exposure-duration effect and the task (bisection or separation discrimination) may work for small separations, it loses plausibility when the larger separation is considered. For that condition, the targets in the separation-discrimination task would have to be detected by local spatial filters whose receptive fields would exceed 5° of visual angle. Even if such large filters existed, it is implausible that the temporal characteristics of local spatial filters with receptive fields larger than 5° would differ significantly from those with

receptive fields slightly smaller than 5'. However, a significant difference would be required to account for the different exposure-duration effects in separation discrimination and bisection within the local spatial filters.

To test whether the same phenomenon is occurring with the 11' and the 2.8° separations, we made a direct comparison between the data in the four conditions (bisection and separation discrimination at 11' and at 2.8°). To facilitate this comparison, we normalized the data for each observer individually by dividing each curve by the threshold value obtained for that condition at the shortest duration (33 ms).

The normalized data are shown in Fig. 3. Small differences in slope are revealed by the difference in the normalized thresholds at the longer durations: for two of the three observers (JB and PA), the bisection data and the separation-discrimination data formed two distinct clusters. For both observers, the normalized separation-discrimination thresholds are higher than the normalized bisection thresholds, regardless of separation. Within each task, the size of the reference separation interacted with the exposure-duration effect, as reported previously, but this interaction was a secondary effect. For observer JM, the data did not cluster by either separation or task. Overall, the data grouped according to task, i.e., bisection or separation discrimination, rather than separation, and it appeared to be much the same for the small as for the large separation. This suggests that a local-spatial-filter model is not the correct explanation for the small separation data.

ANALYSIS OF EXPOSURE-DURATION DATA:
SEQUENTIAL PROCESSING MODEL

Because we could not account for the difference between the bisection and separation-discrimination data in terms of local spatial filters, we looked to the separation discriminator itself. A simple description of the difference between the separation-discrimination and bisection tasks is that separation discrimination involves sequential presentation of the two separations to be compared, whereas bisection involves simultaneous presentation of those two separations. If the separation discriminator can judge two separations simultaneously, then bisection thresholds should always be less than or equal to separation-discrimination thresholds. Lower thresholds might be expected for bisection than for separation discrimination because separation discrimination requires that the observer remember the first separation for comparison with the second, whereas in bisection the comparison is immediate.

The fact that bisection thresholds are higher than separation-discrimination thresholds at short durations suggests that the separation discriminator cannot process the two separations in the bisection task simultaneously. If, instead, the separation discriminator is acquiring information about the two separations sequentially in both tasks, then, in the bisection task, it would have less time for each judgment. The simplest model of this temporal limitation is that the observer has effectively half as much time to process each separation in the bisection task as he has in the separation-discrimination task.

To test this model, we shifted the bisection data to the left

by a factor of two, so that the bisection threshold for a t ms exposure duration was plotted at t/2 ms. The results of this transformation are shown in Fig. 4. Bisection thresholds are now generally less than or equal to the separation-discrimination thresholds, as they should be if processing were identical except for the delay between intervals in separation discrimination.

We assumed that the residual difference was caused by the loss of information between intervals in separation discrimination. Because the time between the intervals was independent of exposure duration, we assumed that information loss was also independent of exposure duration. We assumed further that this information loss was represented by the difference between the bisection and separation-discrimination thresholds that remained when the exposure duration was long enough for performance to have reached its asymptote. On the basis of these assumptions, we took the difference between the bisection threshold at 500 ms (plotted at 250 ms in Fig. 4) and the nearest equivalent separation-discrimination threshold, which is at 300 ms, and subtracted this difference from the separation-discrimination thresholds at all durations. We performed this procedure independently for each observer and each separation.

The results of this transformation are shown in Fig. 5. The thresholds for separation discrimination and bisection now agree closely (except for the large-separation data of Observer JM). Thus the data are consistent with the sequential-processing model: the two separations are evaluated sequentially in both bisection and separation discrimination, but in separation discrimination there is a time lag in which information is lost.

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DEFINING THE BISECTION THRESHOLD

In our presentation of the bisection and separation-discrimination data above, we used a definition of the bisection threshold that is the standard definition in our lab (Burbeck, 1987), but that is not standard in the literature. The two types of definitions are illustrated in Fig. 6. The most commonly used definition, shown in Fig. 6(a), assumes that the observer is comparing the stimulus to an inferred referent in one of two ways:

(1)   A threshold of Δs means that the observer can just detect that the center line is offset by an amount Δs from the mid-position.

(2)   A threshold of Δs means that the observer can just detect that each of the two separations differs by Δs from the average separation, s.

In both interpretations, a threshold of Δs results in a $2\Delta s$ difference between the two separations at threshold.

In the alternative definition, Fig. 6(b), a threshold of Δs means that the observer can just detect a difference of Δs between the two separations. Thus, the comparison-between-separations definition results in a threshold that is a factor of 2 lower than the comparison-to-inferred-referent definition.

The interpretation of the data given above depends heavily on our use of the comparison-between-separations definition. If we used the comparison-to-inferred-referent definition, the bisection thresholds would have been greater than or equal to the separation-discrimination thresholds at all exposure durations. Such a difference could not be accounted for by sequential

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processing. Instead, it would seem to require postulating different mechanisms to account for bisection and separation-discrimination thresholds, with a less sensitive mechanism being used for bisection than for separation discrimination. This is considerably less parsimonious than the sequential-processing model, but it cannot be rejected simply on that account.

We tested the comparison-between-separations definition by comparing bisection and separation-discrimination thresholds using a long exposure duration. The long duration avoids the temporal limitations described.

Methods

We used three bisection paradigms.

Bisection$_t$ The position of the top line was changed ±1-7 units from trial to trial. The positions of the bottom and middle lines were not changed.

Bisection$_m$ The position of the middle line was changed ±1-7 units from trial to trial. This caused each separation to change by the same amount in opposite directions, yielding a difference of 2-14 units between the two separations.

Bisection$_{t\&b}$ The positions of top and bottom lines were both changed by ±1-7 in the same direction. This also caused the difference between the two separations to change by 2-14 units. (Because the position of the entire stimulus

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on the display was changed from trial to
trial, this condition was almost identical to
bisection condition 2. It served primarily as
a check on how effectively we removed edge
cues.)

For comparison with these bisection tasks, we also measured
separation-discrimination thresholds by changing the position of
one of the two lines by ±1-7 units on each trial. Unlike our
previous separation-discrimination tasks, only a single interval
was used in this task. The observer compared the presented
separation to the remembered mean of the previous trials. To
ensure that the eccentricity of the target lines remained the same
as in the bisection task (i.e., that the observer did not fixate
in the middle of the interval), we presented the peripheral test
line with equal likelihood in the upper or lower hemifield. This
separation-discrimination paradigm was similar to $bisection_t$ in
that the difference between the test and reference separations was
1-7 units whereas it was 2-14 units for $bisection_m$ and
$bisection_{t\&b}$. However, in the separation-discrimination task, no
reference separation was presented.

This set of conditions enabled us to determine whether the
displacement of the lines or the separation between them was the
key parameter. If the displacement of the lines were key, then
thresholds should be the same for all four condit. If
separations were being compared, however, then thresholds for
separation discrimination and $bisection_t$ should differ from those
for $bisection_m$ and $bisection_{t\&b}$.

The sequential-processing model assumes that two separations are being compared in both bisection and separation discrimination. Therefore, this model predicts that thresholds for separation discrimination and $bisection_t$ will be a factor of two greater than for $bisection_m$ and $bisection_{t\&b}$, because for a given displacement, the difference between the separations is a factor of 2 less. The model of bisection in which the observer is thought to be comparing the position of the middle line to the mid-position (as defined by the two outer lines) predicts that there will be no difference among the three bisection tasks because all lines are displaced by the same amount. The model of bisection in which the observer is thought to be comparing each of the two separations to the remembered mean predicts that the thresholds for separation discrimination and $bisection_t$ will be $\sqrt{2}$ greater than those for $bisection_m$ and $bisection_{t\&b}$. This follows because, in separation discrimination and $bisection_t$, only one interval conveys information, whereas in $bisection_m$ and $bisection_{t\&b}$ both separations can be compared to the remembered mean and two independent samples yield a threshold that is $1/\sqrt{2}$ lower than the threshold obtained from a single sample.)

We obtained data with a mean separation of 2.8° at a viewing distance of 2.13 m. The exposure duration was 500 ms. Subjects fixated the center of the display screen; no fixation targets were used. The target lines, which subtended 32'x4', were displaced vertically by a random distance in the range ±15' to prevent the top and bottom edges of the screen from being used as a cue to position. No mask was used at stimulus termination.

We obtained data for the four conditions in interleaved

sessions. Each datum is the average of at least 420 trials. All other conditions of the experimental procedures and the data analysis were the same as in the previous experiments.

Results

The data are shown in Fig. 7. The thresholds for separation discrimination and bisection$_t$ are not significantly different. The thresholds for bisection$_m$ and bisection$_{t\&b}$ are a factor of 2 less than those for separation discrimination and bisection$_t$. The solid line is drawn at 1/2 the threshold for bisection$_t$. The dotted line is drawn at $1/\sqrt{2}$ times the threshold for bisection$_t$. The data are consistent with the factor-of-2 difference and inconsistent with predictions of $\sqrt{2}$ difference and no difference. Thus, the comparison-between-separations definition, which predicted a factor-of-2 difference, is well supported. These data do not support models that assume that the observer is either comparing the position of the center line to the mid-position or comparing each separation to the average separation.

In recent years, the comparison-to-referent definition has dominated the literature, but pioneering researchers on bisection in the late 1800's appear to have used the comparison-between-separations definition. Wolf (1923) reports that Volkmann treated bisection as a direct comparison between a variable separation and a standard separation. He further reports that Fisher discovered the factor-of-two difference between bisection and separation discrimination thresholds in 1891.

The type of bisection definition used affects thresholds by a factor of two, and this can have profound effects on the

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interpretation of the results, especially when bisection thresholds are compared to thresholds for other spatial tasks.. To help clarify the literature, we provide a list of bisection studies and the type of definition used.

SITE OF THE EXPOSURE-DURATION EFFECT

We have found that separation-discrimination and bisection thresholds decreased markedly with increasing exposure duration between 33 and 150 ms, regardless of the separation. The difference between the bisection and separation-discrimination data indicates that at least part of this improvement is attributable to the temporal properties of the separation discriminator itself. However, the data do not imply that all (or even most) of the improvement occurs within the separation discriminator. It may be that the exposure-duration effect occurs primarily within the local spatial filters, in the form of temporal contrast integration. If so, then the form of the functions graphed in Fig. 2 is determined primarily by the temporal properties of the local spatial filters and only secondarily by the separation discriminator.

This possibility, however, contradicts the sequential-processing model of bisection, which implies that the separation discriminator is the primary source of the exposure-duration effect. The reasoning is as follows.

Our model of separation discrimination has two stages, local spatial filters and the separation discriminator. Local spatial filters operate on the stimulus in parallel. The effect of exposure duration on the filter outputs will, therefore, be the

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same for bisection and for separation discrimination. (We have already shown that the set of filters that detect the targets in the two tasks do not differ significantly in their temporal properties.) In the sequential-processing model, the two separations in bisection are processed sequentially. Since processing by the local spatial filters is done in parallel, shifting the bisection data by a factor of 2 along the exposure duration axis implicitly assumes that the local spatial filters process the individual targets quickly and that this processing contributes only secondarily to the form of the functions in Fig. 2, under our high contrast conditions.

We assumed that within the local spatial filters, exposure-duration effects are caused by temporal contrast integration, an assumption supported in this context by other studies (Burbeck, 1986; Burbeck and Yap, in press). We then tested the implication that most of the temporal limitation evident in the data occurs in the separation discriminator, and that little occurs in the local spatial filters, by looking at the effect of target contrast on performance of our tasks. We investigated the role of temporal contrast integration in the exposure-duration effect of Fig. 2 by holding the effective contrast of the stimulus constant across exposure durations. We did this by making the stimulus contrast equal to a fixed multiple of the observer's detection threshold at each exposure duration.

Methods

We measured contrast thresholds for the stimuli used in the original paradigm. The center fixation line was presented at 45%

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contrast for 500 + t ms, where t is the target exposure duration
(see Fig. 1). The target line was flashed for t ms, 500 ms after
the onset of the fixation line. In these contrast-detection
experiments, the target line could appear above or below the
fixation line. The observer's task was to report in which
hemifield the target was presented. We varied the contrast of the
target, using the method of constant stimuli, to determine the
observer's contrast-detection threshold. A 90% contrast square-
wave grating mask immediately followed termination of the target,
as in the original experiment. All other conditions, including
the separations and target sizes, were the same as in the original
experiments. Thresholds were calculated, on the basis of 420
trials.

After measuring contrast-detection thresholds for the full
range of exposure durations at both separations, we measured
separation-discrimination and bisection thresholds using stimulus
contrasts that were constant multiples of these detection
thresholds. At each separation, we used the largest integral
multiple that we could and still keep all target contrasts below
50%. (We can achieve no more than 50% contrast for a white line,
because the background on our display is set at half the maximum
luminance.) For the 2.8° separation, we used three times the
detection threshold; for the 11' separation, we used twice the
detection threshold. We could use a larger value for 2.8° than
for 11' because the detection thresholds were lower for the larger
targets of the 2.8° separation.

These separation-discrimination and bisection experiments
were identical to those of the initial experiments, except that

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the contrasts of the targets were held at constant multiples of the detection thresholds. One observer was used. He did not participate in the original experiment.

Results

The contrast-detection thresholds, Fig. 8, show the expected decline with increasing exposure duration. The values are high overall because of the mask that immediately followed presentation of the target.

The separation-discrimination and bisection thresholds obtained with these constant-effective-contrast stimuli are shown in Fig. 9(a). Even with effective contrast held constant, there is a large decline in threshold with increasing exposure duration. Figure 9(b) shows the data after being transformed according to the sequential-processing model. (The bisection thresholds were shifted to the left by a factor of 2. There was no residual difference at 250 ms.) The results of this transformation are similar to those in Fig. 2. Thus, contrast integration appears not to have been a major factor in the original paradigm.

As a final confirmation, we collected additional data on this observer to determine the extent to which these constant-effective-contrast data differed from the data that would have been obtained in the high-contrast conditions.

At the shortest durations, the contrasts used in the constant-effective-contrast experiments were close to 45% (41 and 37% respectively for the 11' and 2.8° separations). Thus, increasing the contrast to 45% would have little effect at the shortest durations. At the longest durations, the contrasts used

were much less than 45% (approximately 10% for both separations). Thus, increasing the contrast at the long durations could have a substantial effect. We measured separation-discrimination and bisection thresholds using the 45% contrast targets with a 500 ms duration and compared them to the data from the constant-effective-contrast experiments. This comparison provides an upper bound on the overall effect because increasing contrast at shorter durations would decrease thresholds, if it had any effect at all, which would reduce the effect of exposure duration.

The results are shown by the symbols in Fig. 9(c). The constant-effective-contrast data for this observer are shown by the solid and dashed lines. For the large separation, increasing contrast had at most a small effect. For the small separation, contrast had a larger residual effect. However, in neither case could the primary effect of increasing exposure duration be attributed to contrast integration. The exposure-duration effect was essentially as large with stimuli of constant effective contrast as with stimuli of constant high nominal contrast. These findings lend additional support to the sequential-processing model of bisection, and indicate that the functions in Fig. 2 are reasonably accurate representations of the temporal characteristics of the separation discriminator.

Site of the Masking Effect

In the experiments described above, we presented a masking stimulus at the termination of each test stimulus to interrupt processing. The sequential-processing model of bisection implicitly assumes that the mask interrupted processing within the

separation discriminator itself. This assumption is supported by the results of the constant-effective-contrast experiments. If the mask had not interrupted processing within the separation discriminator, then the equal-strength stimuli would have resulted in equal separation-discrimination thresholds, which they did not (see Fig. 9).

The assumption that the mask interrupts processing in the separation discriminator has another testable implication. Within the local spatial filters, the effect of the mask is the same for separation discrimination and bisection, because the stimuli are locally similar. However, if the separation discriminator operates serially, as the sequential-processing model asserts, then for a given exposure duration, the mask should have a different effect for bisection, which requires two separation discriminations, than for separation discrimination, which requires only one within that duration. We tested this prediction experimentally.

Methods

We measured separation-discrimination and bisection thresnolds for a $2.8°$ separation u_ _ _g a 33-ms exposure duration with and without a mask. Contrast was set to three times the detection threshold for each condition. We also obtained data using a 500-ms exposure duration with contrast set to three times the detection threshold for the masked stimulus and set to 45% for the unmasked stimulus. Each datum is based on at least 420 trials. All other conditions of the experiment were the same as in the previous separation-discrimination and bisection

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experiments.

Results

The results of the 33-ms exposure duration experiments are shown in Fig. 10. When no mask was used (open bars), there was little difference between the thresholds for bisection and separation discrimination. Separation-discrimination thresholds were only slightly higher. However, when the mask was used (lined bars), task had a large effect: the bisection threshold was twice as high as the separation-discrimination threshold for the same condition. The data for 500-ms exposure duration, which are not shown, yielded no effect of mask for either task.

The interaction between the task and the effect of the mask, evident in the data of Fig. 10, implies that the primary effect of masking is to terminate processing within the separation discriminator (because the effect of the mask within the local spatial filters is independent of task). The factor-of-2 difference between the bisection and separation-discrimination thresholds in the masked condition could occur because the observer acquires only one separation in the 33-ms presentation time and compares this separation to a remembered mean separation. [We have seen above that comparison to this remembered mean is almost as accurate as comparison to a presented mean. This has also been reported previously (Burbeck and Swift, 1988).] The results of this experiment indicate that masking is indeed occurring within the separation discriminator. Thus, these results support the sequential-processing model of bisection.

The data on the effect of a mask also tell us something else

of importance: The separation discriminator does not depend on the presence of the target for continued processing. Bisection thresholds equaled separation-discrimination thresholds with the 33 ms unmasked target even though 33 ms is not long enough for the separation discriminator to process two separations accurately. Apparently if there is no masking stimulus, input to the separation discriminator continues well after the stimulus itself has been extinguished.

SUMMARY AND DISCUSSION

We have found that exposure duration has a different effect on bisection thresholds than on separation-discrimination thresholds. Bisection thresholds decrease more between 33 ms and 150 ms than do separation-discrimination thresholds. This difference can be accounted for by a model in which bisection is done by encoding the two separations sequentially. This sequential-processing model relies on a definition of the bisection threshold that assumes that the observer compares (either sequentially or in parallel) the two separations created by the three lines in the bisection stimulus. Direct comparison of bisection and separation-discrimination thresholds supports this definition. The sequential-processing model of bisection is further supported by data showing that the effect of exposure duration on separation-discrimination and bisection thresholds cannot be attributed to temporal contrast integration. Also, consistent with our model, we have found that the primary effect of a mask in our high-contrast conditions was to interrupt extraction of information about the separation between the

targets,not to interrupt processing of the individual targets.

These results were not specific to the large separation condition. The data obtained using an 11' separation exhibited the same properties as did those obtained using a 2.8° separation, except for the small separation, where exposure duration continued to have an effect for durations between 150 and 500 ms and where contrast had a larger effect. The difference in exposure-duration effects has been reported previously (Burbeck, 1986; Yap, Levi, and Klein, 1987). Burbeck argued that the difference is attributable to differences in the temporal characteristics of the relevant local spatial filters: the local spatial filters that detect the individual targets are smaller for small separations than for large ones, and smaller local spatial filters have longer temporal integration times. The temporal integration that occurs within the local spatial filters is contrast integration, so this explanation of the exposure-duration effect predicts that contrast should also have more effect at small separations than it does at large separations, which is exactly what we find.

Apart from small differences that are consistent with previous findings and conclusions, the data for the large and small separation are remarkably similar. They show no suggestion that separation judgments are mediated by a different mechanism for small separations than for large ones. Specifically, the data reported here do not support the theory that small separations are encoded directly by the local spatial filters, as has been proposed (Wilson and Gelb, 1984; Klein and Levi, 1985, 1987; Yap, Levi, and Klein, 1987, 1989; Levi, Klein, and Yap, 1988).

Sequential processing has previously been observed in another spatial-position task. Meer and Zeevi (1985) measured thresholds for detecting the nonalignment of a dot relative to the virtual intersection of a horizontal and vertical line. They found that a short exposure duration (200 ms) resulted in a high threshold, and a long exposure duration (2000 ms) resulted in a hyperacuity threshold, whereas for a single alignment task, they found no exposure-duration effect. They concluded that the two alignment judgments were occurring sequentially.

Our results and conclusions are not in agreement with Sagi and Julesz's (1985) general statement that "where" an object is, is processed in parallel across the visual scene. However, their task was a complicated one, involving detection of the form of a triangle from the relative positions of its vertices. It is not clear exactly what cues the observer used in their task. Comparison of the two studies raises the interesting question of what the relationship is between the mechanism underlying acute separation discriminations, i.e., the separation discriminator, and the mechanism(s) responsible for our immediate, but less accurate, representation of the relative positions of the many objects that constitute our normal visual environment.

ACKNOWLEDGEMENT

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Figure Captions

Figure 1   Schematic diagram illustrating the temporal and
spatial configurations used in the initial
separation-discrimination and bisection experiments.

Figure 2   Thresholds for separation discrimination and
bisection as a function of exposure duration for two
separations, 2.8° and 11'. Data were obtained for
three observers. When no error bar is evident, the
extent of error was smaller than the symbol.

Figure 3   Thresholds for separation-discrimination and
bisection normalized to the 33 ms threshold value.

Figure 4   Comparison of separation-discrimination thresholds
with bisection thresholds that have been shifted to
the left along the horizontal axis by a factor of 2.

Figure 5   Comparison of separation-discrimination and
bisection thresholds after each has been transformed
according to the sequential-processing model. The
bisection thresholds have been shifted to the left
by a factor of 2 and the separation-discrimination
thresholds have been reduced by the 250-ms-residual
difference, Δ_{250}. See text for a detailed
explanation.

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Figure 6   Schematic illustration of three interpretations of
                  the bisection threshold. The comparison-between-
                  separations definition is used in this paper.

Figure 7   Thresholds for separation discrimination and for
                  three bisection conditions. In bisection$_t$ the
                  position of the top line was changed; in bisection$_m$
                  the position of the middle line was changed; in
                  bisection$_{t\&b}$ the positions of the top and bottom
                  lines were changed in the same direction. In all of
                  the tasks, the threshold shown corresponds to the
                  extent of displacement of one or more lines,
                  regardless of the effect on the separation. The
                  solid line corresponds to half the bisection$_t$
                  threshold and the dashed line corresponds to the
                  bisection$_t$ threshold divided by $\sqrt{2}$.

Figure 8   Contrast-detection thresholds for the line stimuli
                  used in the first experiment, measured as a function
                  of exposure duration.

Figure 9   (a) Separation discrimination and bisection
                  thresholds for two separations measured as a
                  function of exposure duration. The effective
                  contrasts of the stimuli were equated by making the
                  stimulus contrasts equal to a constant multiple of
                  the detection threshold for that duration and
                  separation. Contrast was twice the detection
                  threshold for the 11′ separation, and three times

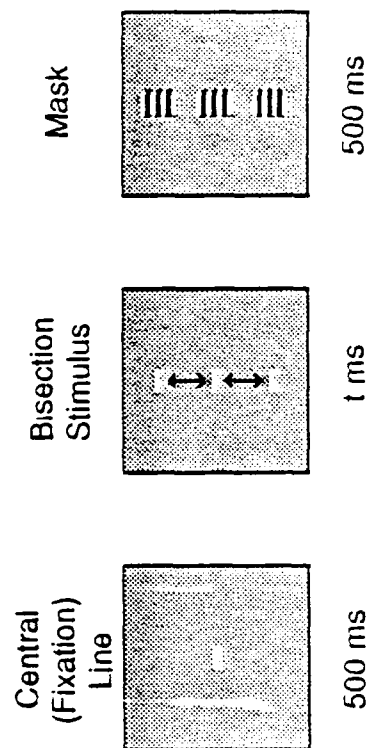the detection threshold for the 2.8° separation.
(b) The same separation discrimination and bisection
thresholds after being transformed according to the
sequential-processing model. (c) The symbols show
separation-discrimination and bisection thresholds
for 500 ms duration, measured with high contrast
stimuli. Error bars do not show because they are
smaller than the symbols. The solid and dashed
lines are the constant-effective-contrast data for
this observer from Fig. 9(a).

Figure 10   Effects of presenting a mask at termination of a
briefly flashed stimulus in bisection and separation
discrimination. The no-mask conditions are shown by
the open bars, the mask conditions by the lined
bars. Thresholds were measured at three times the
detection thresholds for the mask and no-mask
conditions.
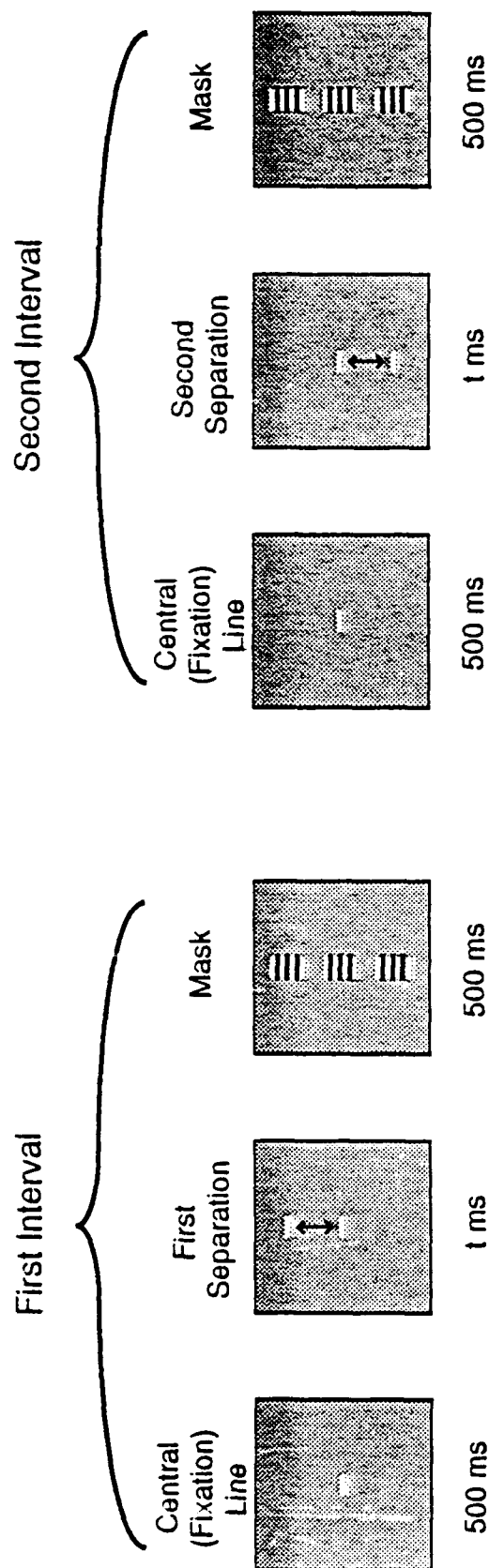
Christina A. Burbeck and Yen Lee Yap
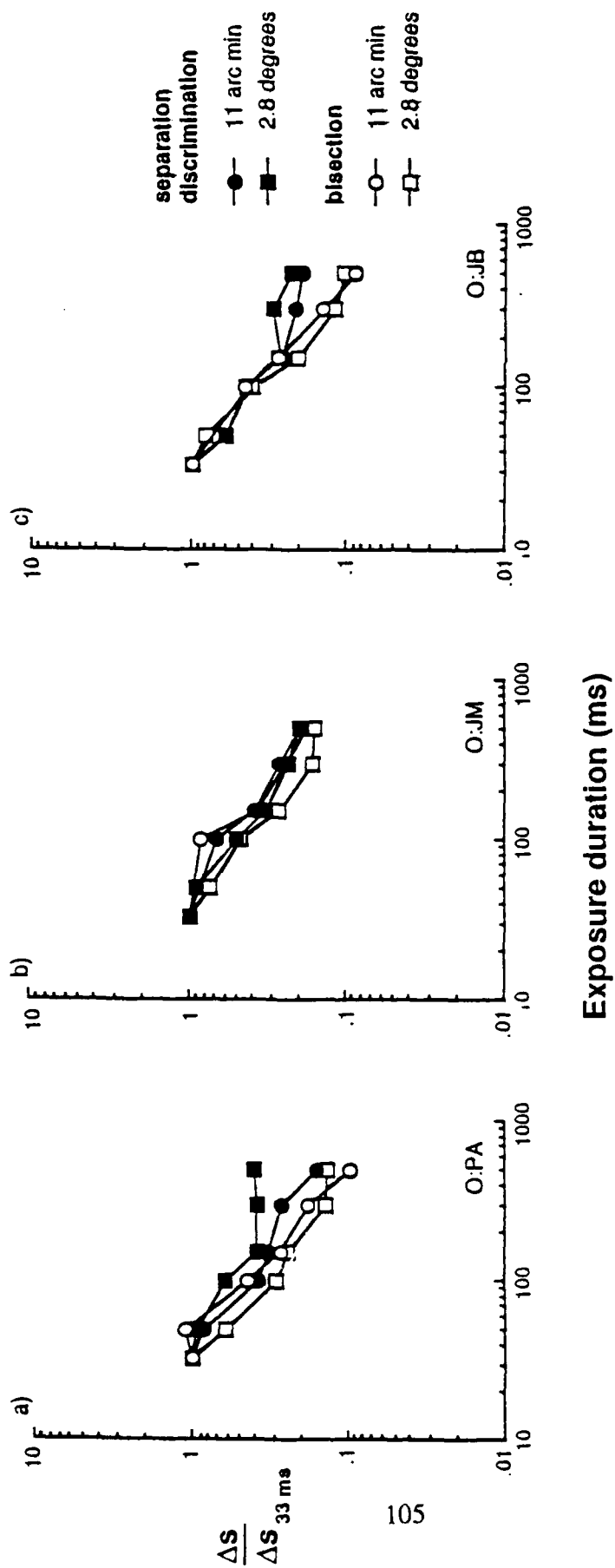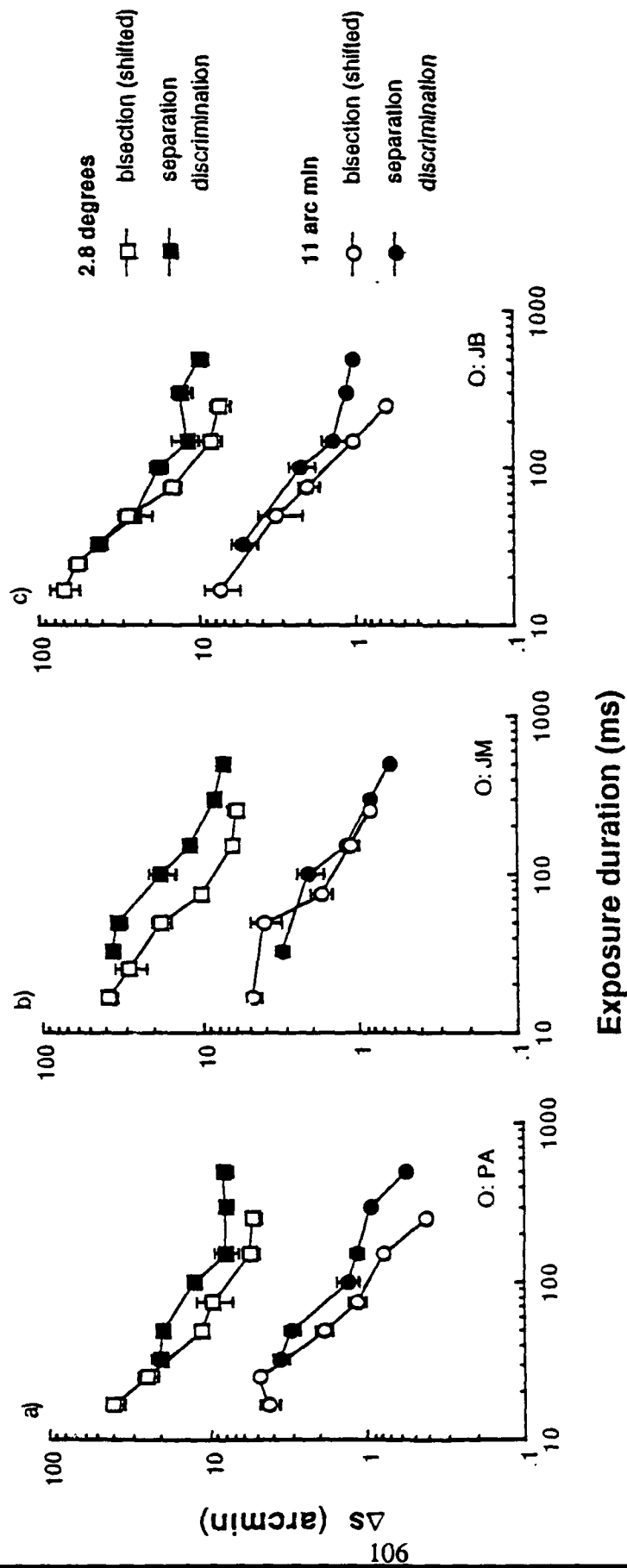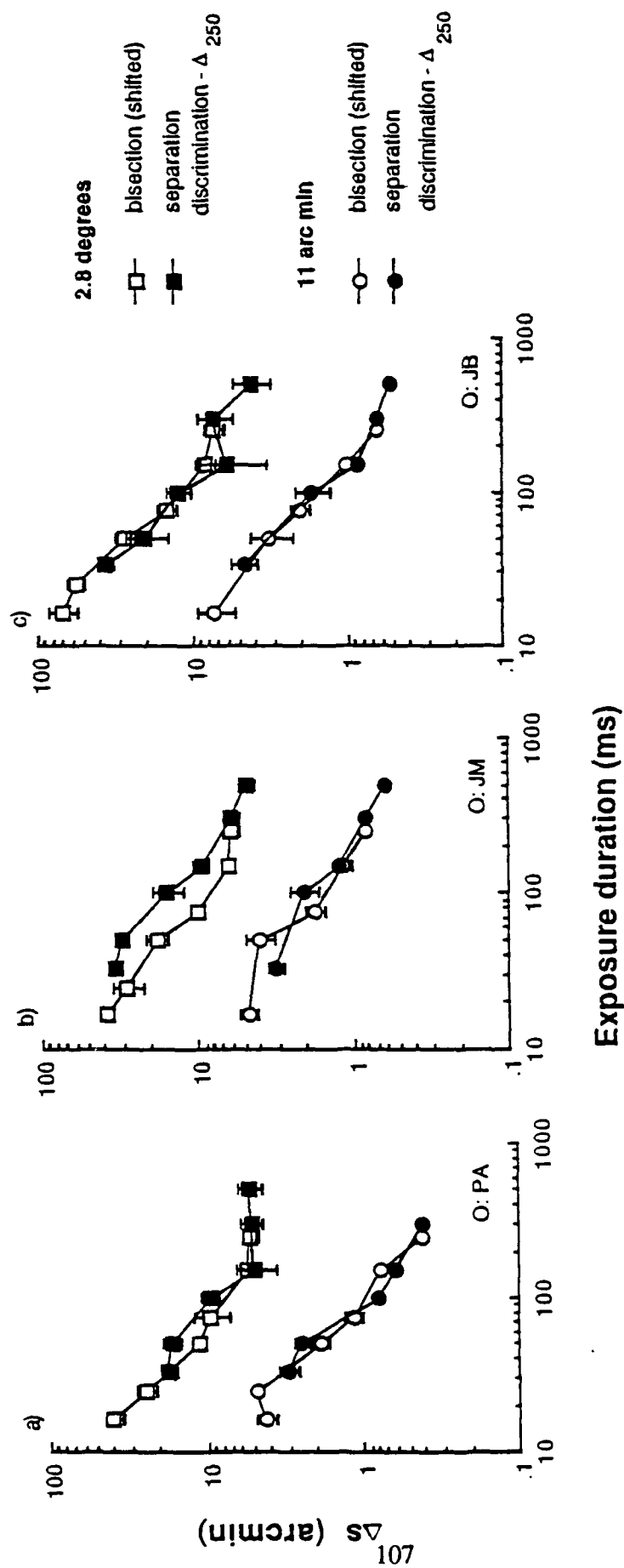"Spatiotemporal Limitations in *Localization*"
Fig. 1

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"Spatiotemporal Limitations in Localization"
Fig. 2

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"Spatiotemporal Limitations in Localization"
Fig. 3

Christina A. Burbeck and Yen Lee Yap
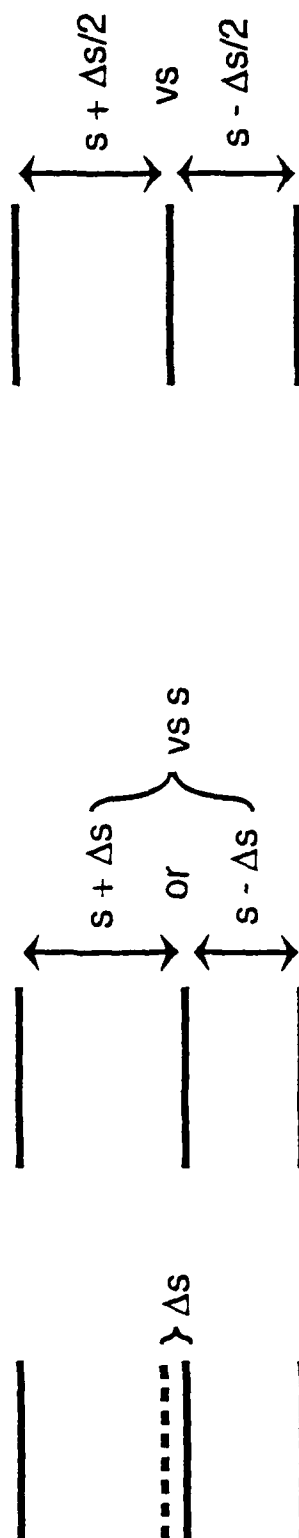"Spatiotemporal Limitations in Localization"
Fig. 4

Christina A. Burbeck and Yen Lee Yap
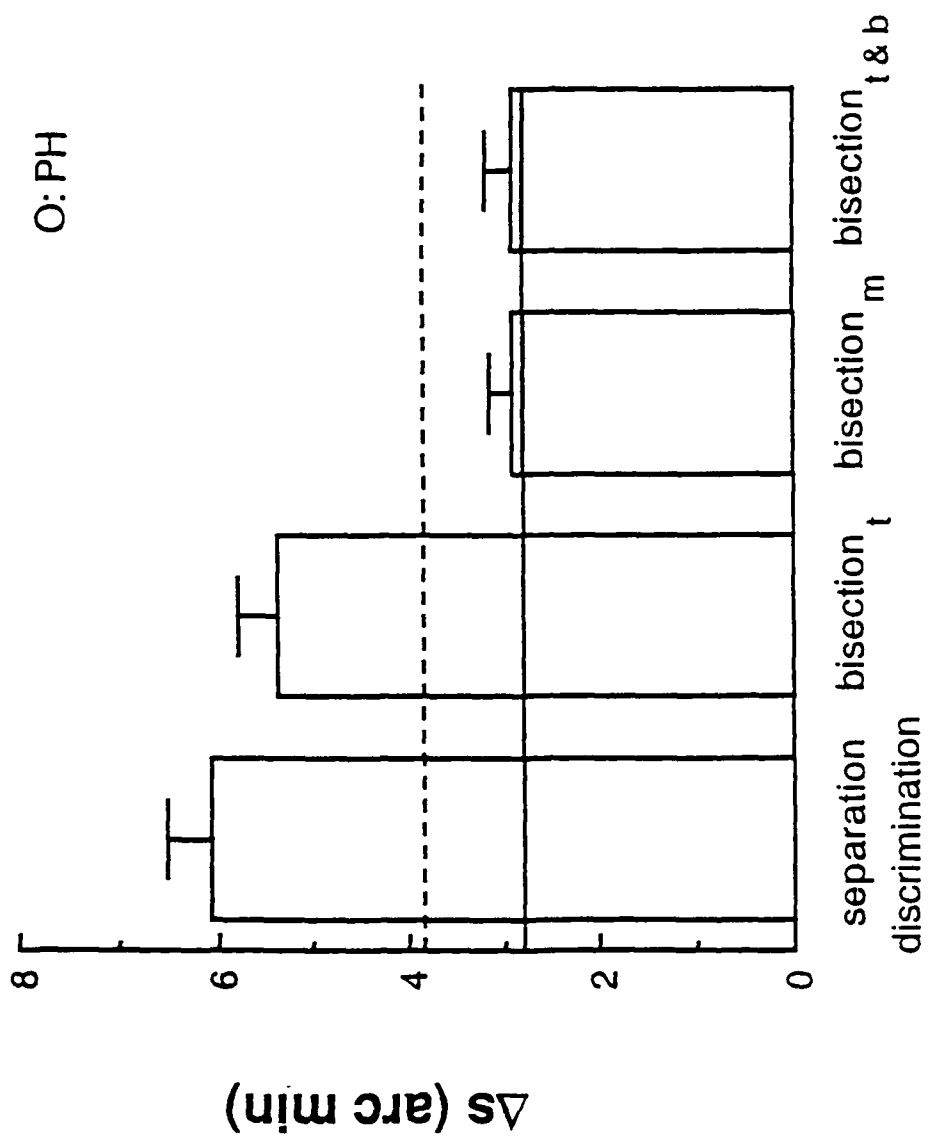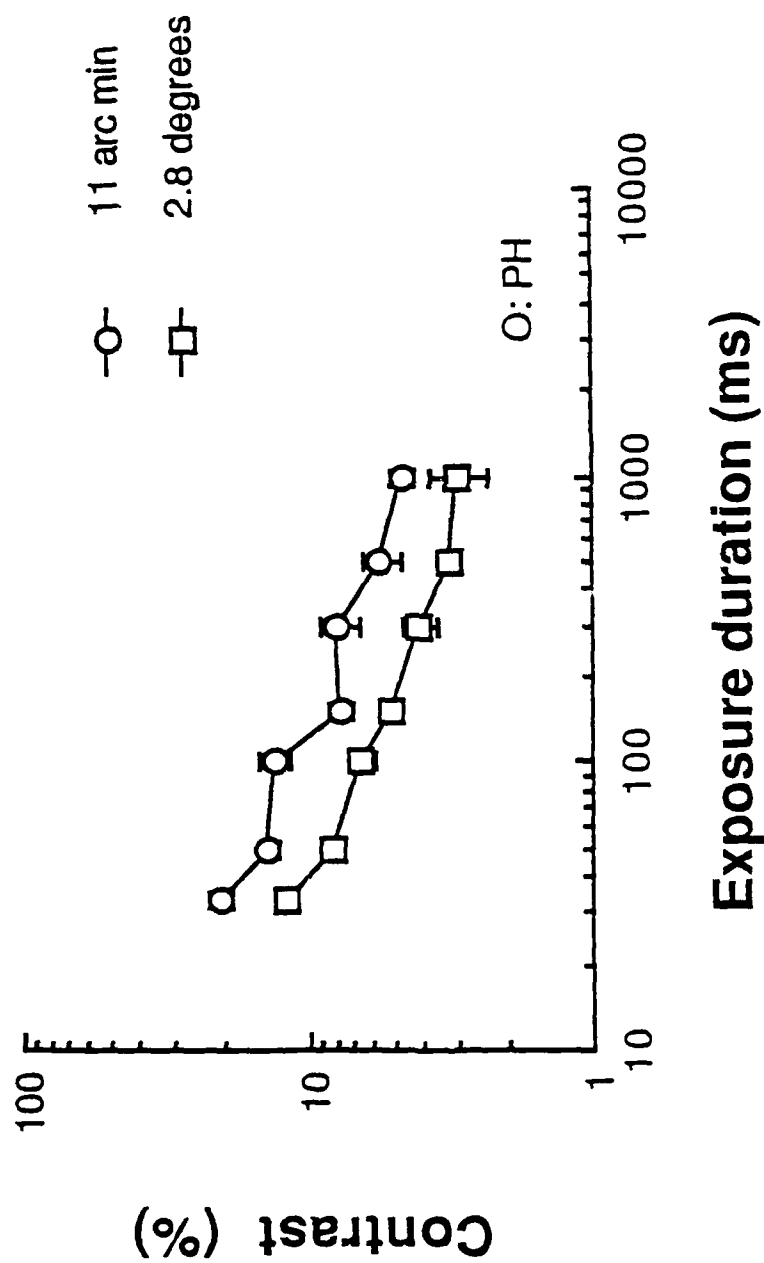"Spatiotemporal Limitations in Localization"
Fig. 5

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a) Comparison to Inferred Referent

Comparison to midpoint

Comparison to mean separation

$s + \Delta s$ or $s - \Delta s$ vs s

Δs

b) Comparison Between Separations

$s + \Delta s/2$ vs $s - \Delta s/2$

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"Spatiotemporal Limitations in Localization"
Fig. 6

O: PH

Δs (arc min)

Task

separation
discrimination

bisection$_t$

bisection

bisection$_m$

bisection$_{t \& b}$

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Fig. 7

Exposure duration (ms)

Contrast (%)

11 arc min

2.8 degrees

O: PH

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"Spatiotemporal Limitations in Localization"
Fig. 8

a)

100

10

1

.1

2.8 degrees
□— bisection
■— separation discrimination

11 arc min
○— bisection
●— separation discrimination

O: PH

10   100   1000   10000

b)

100

10

1

.1

2.8 degrees
—□— bisection (shifted)
■— separation discrimination

11 arc min
○— bisection (shifted)
●— separation discrimination

O: PH

10   100   1000   10000

Δs (arc min)

c)

100

10

1

.1

2.8 degrees
□   bisection (45% contrast)
■   separation discrimination (45% contrast)

11 arc min
○   bisection (45% contrast)
●   separation discrimination (45% contrast)

O: PH

10   100   1000   10000

Exposure duration (ms)

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"Spatiotemporal Limitations in Localization"
Fig. 9

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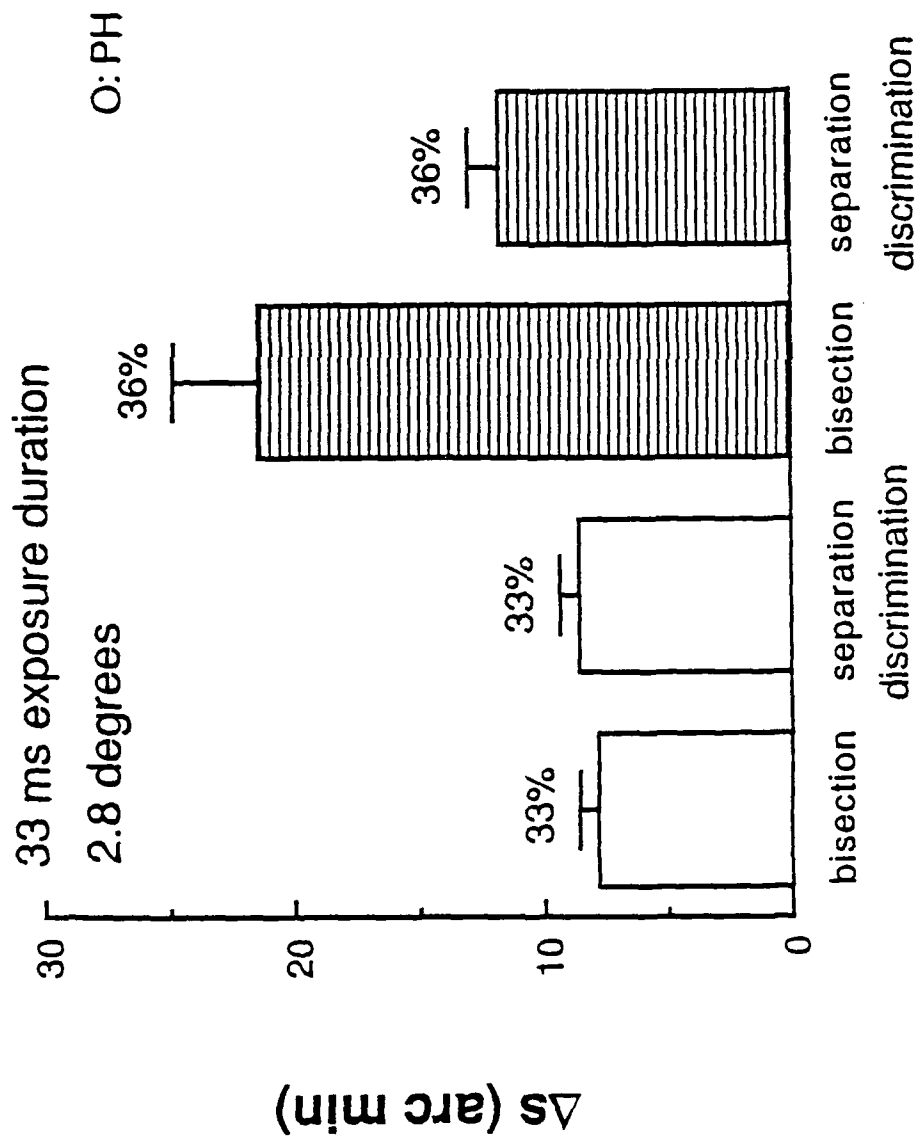
Christina A. Burbeck and Yen Lee Yap
"Spatiotemporal Limitations in Localization"
Fig. 10

Table 1 Lists of studies using each of the two definitions of the bisection threshold. The comparison-to-inferred-referent threshold is a factor of 2 smaller than the comparison-between-separations threshold.

Comparison to Inferred Referent	Comparison Between Separations
R. Fischer, 1891 (as cited by Wolfe,1923)	Volkmann, 1860 (as cited by Wolfe,1923)
Wolfe, 1923	Andrews & Miller, 1977
Bedell, Johnson, & Barbeito, 1985	Burbeck, 1987
Levi & Klein, 1983	
Klein & Levi, 1985, 1987	
Levi, Klein, & Yap, 1987, 1988	
Toet, van Eekhout, Simons, & Koenderink, 1987	
Yap, Levi, & Klein, 1987 a,b	
Toet & Koenderink, 1988	
Lindblom & Westheimer, 1989	

Appendix D

SPATIAL INTERACTONS IN RAPID PATTERN DISCRIMINATION

Ben J.A. Kröse and Christina A. Burbeck

Spatial interactions in rapid pattern discrimination

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Abstract

We measured reaction times (RTs) for identification of a target among distracters under stabilized image conditions in which the positions of the target and the distracters were constant within a single experimental session. Under these conditions, the observer need not search for the target because its position is known. We nevertheless found that the presence of even a single distracter could elevate RTs. The magnitude of this effect depended on the distance of the distracter from the target and, for some observers, the distance of the distracter from the fovea. When we added not one but six background elements in a ring around the target, RT increased even more. If, apart from these neighboring distracters, the target was surrounded by more distracters located beyond the nearest neighbors, RT was, in general, not increased further. These findings suggest that adding background elements in a search task can elevate RTs in ways that are not dependent on the positional uncertainty of the target.

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Introduction

Reaction time procedures have been widely used to study the detectability of a target element in a display of nontarget elements. Specifically, experiments often measure RT as a function of the number of elements in the field, under the assumption that if RT increases with increasing number of elements, then the observer has engaged in a serial search, whereas if there is no such increase, then the elements have been processed in parallel (Treisman and Gelade, 1980; Bergen and Julesz, 1983; Pashler, 1987; Wolfe et al. 1988). This interpretation is supported by the finding that target detectability improves substantially if the observer knows in advance the location of the target, suggesting that the observer is able to direct his attention and process information from this location selectively (Engel, 1971; Eriksen and Hoffman, 1972; Posner, 1980; Kröse and Julesz, 1989).

Complicating this interpretation, however, is the finding that even if the target is presented at a fixed position, so that no "search" is necessary, the addition of more background elements can influence target detectability (Eriksen and Eriksen, 1974). Eriksen and Eriksen (1974) measured RT's for the identification of a target letter (always presented 0.5° above the fixation point) which was flanked by noise letters (3 left, 3 right) and found RT's elevated by the presence of the noise letters. More specifically, they found effects of target-noise similarity and of the between-letter spacing, for spacings up to about 0.5°. Whatever mechanism orients attention to the expected location of the target is apparently not able to ignore completely the activity at the nontarget locations. The experiments reported here examine the effects of such distracters with a peripherally located target. Our specific aim was to get a sense of the magnitude and extent of these distracter effects for a nonfoveal target, as compared to the results reported in the literature for a foveal target, looking in particular at the effect of the spacing between the target and the distracter and the effect of the retinal position of the distracter.

Bouma (1970) previously studied lateral interactions in the identification of a peripherally presented letter (between 1.5° and 10° eccentricity). His results show that the size of the area within which noise letters (1 left, 1 right) interact is approximately equal to 0.5 times the eccentricity at which the target is presented. However, in his experiments there was uncertainty about the target position; the target could occur either to the right or to the left of the fixation point. Because the observer could not attend to a single retinal location, the data from his experiments may exaggerate the magnitude of the interactions.

In our experiments, the target was always presented at a fixed location (3° above the fovea). Image stabilization was used to ensure consistent target placement without requiring the observer to foveate a fixation mark. This is important because deliberate foveation requires attention, and we wanted the observer to attend to the target location, not the fovea. This technique is also preferable, for our purposes, to the use of a visual cue with multiple possible locations, because the cue itself draws attention, and we wished to determine the extent to which the observer could direct his attention without a visual trigger, as he must do if he is searching for a target.

Methods

Stimuli were presented on a Macintosh Plus computer, which also served to measure RTs and percentage of errors. The stimuli were stabilized on the retina by an SRI Dual-Purkinje Eyetracker, Generation V, with stimulus deflector (Crane and Steele, 1985; Crane and Clark, 1978). All experiments were conducted with stabilized images.

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The target and distracter elements were either $\cup$'s or $\cap$'s, 0.47° in height and 0.30° in width. They were white (equal to the luminance of the background) and were presented on dark disks. Each disk subtended 0.78° of visual angle. These elements were similar to the ones used by Julesz et al. (1973) and have the property that a texture field composed of $\cup$'s can not be discriminated effortlessly from a texture field composed of $\cap$'s. See Figures 1, 3, and 4 for examples of the stimuli. The mean luminance of the background was approximately 40 ft.L., maintaining photopic conditions. The background subtended 9.8x18.8° at the 50.5-cm viewing distance (measured from the second servo-driven mirror of the stimulus deflector, which is optically conjugate with the pupil).

The target was always presented in the same spatial position, 3.1° above the fovea on the vertical meridian. The stimuli came on abruptly and remained on until the observer responded. No fixation mark was needed during the experiments because the stimulus was stabilized on the retina. The target was present on every trial and the observer had to report, as rapidly as possible (while maintaining a constant low level of errors), whether he saw a $\cup$ or a $\cap$ by pressing one of two keys on keyboard. Depending on the experimental condition, one or more distracters could be presented simultaneously with the target. The number and positions of the distracters were constant during a single experimental session. The observer distinguished the target from the distracters only by its position. Each distracter was randomly and independently chosen to be a $\cup$ or a $\cap$ on each trial.

A block consisted of 110 trials. The RTs of the first 10 trials of each block were not used in calculating the average, but served as a brief practice. After eliminating the trials in which an

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incorrect response was given, we calculated the geometric mean RT of all trials in the block, regardless of whether a ∪ or a ∩ served as the target. Extensive practice was done before collecting any of the data included in the main body of this report. The results of the practice sessions are shown in Appendix A.

Before each block of trials, a fixation point was presented in the center of the display. The observer adjusted the offset of the stimulus deflector to make this fixation point coincident with his center of gaze (and, we assume, coincident with the center of his fovea). The fixation point disappeared prior to the first trial and did not return until the end of the last trial in the block, when the observer confirmed that it still coincided with his center of gaze. (It always did.)

Care was taken to randomize the order in which data were collected for the different conditions, in case there were residual learning effects. In addition, we measured RT for the *no-distracter* condition several times each day and used that as the baseline for that day's data. (Preliminary experiments showed that RT's fluctuate from day to day even after the initial learning period is over. See Appendix A.) Performance is expressed as the difference between the RT with distracter(s) and the average no-distracter RT for the day. Data were obtained from at least three 110-trial blocks for each condition, unless indicated otherwise.

Target-Distracter Spacing and Relative Position

We measured RT with and without a a single distracter. The distracter was placed at one of six positions at one of five distances from the target. The six distracter positions used in the experiment are shown in Figure 1, where a distracter is placed at Position 1 as an example. The position of the target was fixed. The position of the distracter was fixed during an experimental

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session and was varied between sessions. We found that RT's obtained with background elements to the left of the target were, in general, not significantly different from RT's obtained with background elements to the right of the target. Therefore, the data were averaged across the left and right positions. Positions 1 and 2 are above the target and have a larger eccentricity than the target, Positions 0 and 3 are beside the target and have a similar eccentricity, and Positions 4 and 5 are below the target and have a smaller eccentricity.

Results for three observers are shown in Figure 2. Observer B was tested on 4 blocks per condition, Observers A and C, three blocks per condition. The vertical scale is the same for all observers to facilitate comparison across observers.

There are large and consistent intersubject variations in the effect of a single distracter. Observer A is less sensitive to a distracter than are Observers B and C. A two-way (position x spacing) analysis of variance (ANOVA) applied to the data of Observer A shows that the effect of position is not significant [$F(2,75)=1.25$, $p>.25$] and that the effect of spacing is also not significant [$F(4,75)=1.52$, $.10<p\leq.25$]. However, for Observer B, both the effects of position [$F(2,105)=3.96$, $.01<p\leq.025$] and spacing [$F(4,105)=4.37$, $.0001<p\leq.005$] are significant. For Observer C, the effects of spacing and position are even more prominent [effect of position, $F(2,75)=17.5$, $p\leq.0001$; effect of spacing, $F(4,75)=8.28$, $p\leq.0001$].

For Observer C, who showed the largest effects, a distracter placed below the target (i.e., nearer the fovea) has a larger effect than does one next to or above the target. This is consistent across

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spacings and is not attributable to the order of presentation, which was randomized. This pattern, together with the natural association between attention and foveation, suggested the following experiment in which we examined the effect of the retinal position of the distracter.

Retinal Position of Distracter

Although the background elements at Positions 4 and 5 (Figure 1) are near the fovea for spacings of 2° or 3°, they are never closer than 1.5° from the center of the fovea. To get more information on the effect of a foveal distracter and to determine the effects of the retinal positions of the distracters more systematically, we used a different set of positions. Spacing between the target and distracter was fixed at 3.1°. Distracter position was varied from $\varphi = 0°$, distracter to the right of the target, to $\varphi = -180°$, distracter to the left of target, in seven equally spaced steps along an equidistant arc below the target, as shown in Fig. 3a. At $\varphi = -90$ the distracter is presented at the fovea. Results are shown in Figure 3b for four observers – Observers A and B, who participated in the previous experiment and two other observers who were also experienced at this type of task. Observer D was tested on 3 blocks per conditions, Observers A and E, 4 blocks each, and Observer B, 5 blocks per condition. The number of blocks used depended on the variability of the observer's responses.

—————————Insert Figure 3 about here —————————

For Observers D and E, a single background element located on or near the fovea had a large effect on RTs. The analysis of variance on the effect of position shows that this effect is significant for both observers: Observer D [$F(6,14)=10.1$, $.0001 <p<=.005$] and Observer E [$F(6,21)=2.97$, $.025<p<=.05$]. An increase in RT also occurred for Observer B, but the effect was relatively small

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and not significant (effect of position [F(6,28)=1.56, p>.25]). For Observer A , there was no significant increase in RT for the foveally-presented distracter [effect of position, F(6,21)=1.49, 10<p<.25]. The lack of effect for Observers A and B was not caused by long RT's in the no-distracter condition. Observer A, who showed the least effect of the single distracter, had the shortest RT's of all observers (mean no-distracter RT of 435 ms). Thus, there appears to be large systematic inter-observer differences in the effect of a distractor presented foveally. For some observers, a distractor placed on the fovea is much more distracting than one placed off of the fovea; for others, it has no preferential effect. This difference was not immediately attributable to any other characteristics of the observers.

Surrounding the Target with Distracters

To learn more about the effect of increasing the number of distracters, we surrounded the target element by background elements, as shown in Figure 4. There were either six background elements, arranged in a hexagonal "one-ring" configuration around the target, as shown in Figure 4a, or eighteen background elements arranged in a "two-ring" configuration, as shown in Figure 4b. Reaction times for identification of the target, whose position was always know, were measured and compared to the no-distracter condition. The spacing of the target-distracter array was a parameter of the experiment. With a hexagonal arrangement, the distance between any two adjacent elements is constant for a given spacing; thus, for example, a spacing of 1.2° means that the distance between any element (target or distracter) and its nearest neighbor was 1.2°.

——————————————Insert Figure 4 about here——————————

The number of background elements (6 or 18) and the spacing were kept constant during a block (110 trials). RT's for the "one-ring" condition were measured for spacings ranging from 1.2° to

4.8°. RT's for the "two-ring" condition were measured for spacings ranging from 1.2° to 2.4° because of limitations imposed by the display size. Observers A and C were tested on 3 blocks of trials, and Observer B on 4 blocks.

———InsertFigure 5 about here ———

The results are shown in Figure 5, where we plot the increase in RT as a function of spacing for the one- and two-ring conditions. As a comparison, we also show the maximum RT elevation obtained on the one-distracter condition (as reported in Figure 2).

For Observer A, RT is elevated only slightly by the rings of distracters. For Observer B, RT is significantly elevated by the rings, even at large spacings. For Observer C, RT's are elevated markedly by the rings at small spacings and are elevated somewhat at large spacings. For all three observers, the rings at small spacings produce the largest ΔRT's. These effects are always larger than the maximum ΔRT's produced with a single distracter.

The effect of adding six background elements instead of one is small for Observer A, consistent with the small effects obtained for her with a single distracter. However, the effect of the ring is large for the other two observers. A two-way ANOVA (number of distracters x spacing) applied to the data for spacings less than 2.4°, shows for Observer A [$F(1,35)=0.516$, $p>.25$], Observer B [$F(1,50)=19.2$, $p\leq.0001$], and for Observer C [$F(1,35)=10.9$, $.0001 <p\leq.005$]. The effect of spacing (a two-way ANOVA, condition x spacing) is significant for all three observers: Observer A [$F(2,27)=2.96$ $.05 <p\leq.10$], Observer B [$F(2,39)=7.25$, $.0001<P\leq.005$] and Observer C [$F(2,27)=20.0$, $p\leq.001$]. The effect of adding the second ring (two-way ANOVA, number of rings x spacing, applied to the data for spacings less than 2.4°) is not significant for Observers C

[F(1,12)=.43, p>.25] and A [F(1,12)=1.4, p>.25] but is significant for Observer B [F(1,18)=19.99, .0001<p≤.005].

The results of this experiment indicate that adding background elements farther away than the nearest neighbor usually does not affect RT. However, if the number of nearest neighbors is increased from one to six, RT's generally increase.

Discussion

Even though the target was presented at a fixed retinal position during the entire experiment, so that the observer was certain of its location (both relative to the display edges and absolutely on his retina), there was still a significant effect of the distracters for all except one observer. This effect appears to depend, at least in some observers, on the spacing between the distracters and the target, and on the retinal position of the distracter relative to the fovea.

Results presented in Figure 2 show that a single background element has at most a small effect if it is presented at a larger eccentricity than the target, even if it is relatively close to the target (1.2° was our smallest value). However, a single background element presented at the same (or smaller) eccentricity than the target can have a significant effect, the magnitude of which depends on the spacing between the target and the distracters and on the characteristics of the observer. When this single background element is presented on the fovea, there can be a large increase in RT. The inter-observer variation seen in these effects did not appear to be related to the amount of practice the observer had at this task or to the observer's general level of experience in psychophysical experiments.

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Two previous studies have reported effects of distracters that were dependent on the spacing between the distracters and the target. In both of these studies, the exact target location was not known to the observer. In the Bouma (1970) study mentioned above, the target could occur in either of two widely separated locations, so that the observer could not attend to the target location prior to stimulus presentation. Sagi and Julesz (1985) also report spatial interactions of the type seen here, in their study comparing the identifiability of a single target to the discriminability of two targets. They found that the second target masked the first when the two were separated by less than 2° for a target eccentricity of 4°, and when they were separated by less than 6° for a target eccentricity of 12°. In their task, the observer had to attend to both targets and the position of the targets varied randomly from trial to trial. In our experiments, the observer knew the target location exactly. Nevertheless, the spatial extent of the interactions we found is not smaller than they found. Thus, knowing the target location in advance does not appear to diminish the extent of the effects.

Lateral effects outside the classical receptive field (CRF) have also been found electrophysiologically. There is increasing evidence that for many visual neurons, stimuli presented outside the CRF strongly and selectively influence responses to stimuli presented within the CRF (for a review, see Allman et al., 1985). For example, a moving background strongly affects the direction and velocity tuning of many cells in the middle temporal area (Allman et al., 1985) and in Areas V1 and V2 (Allman et al., 1988) of the owl monkey. DeYoe et al. (1986) have reported analogous surround effects using static texture patterns in Area V1 and V2 of macaque monkeys. In their experiments, texture background often suppressed the response to a target within the CRF, sometimes in an orientation-specific manner. It is unknown whether these interactions are caused by intrinsic connections or by the many descending pathways (Maunsell and Van Essen, 1983) from higher cortical areas.

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Such intrinsic connections within a cortical area might account for some of our data, but they do not readily explain the foveal effects we found, which vary profoundly among observers. The effects we observed in our experiments may be nothing else than an involuntary shift of attention, caused by the foveal stimulus. It has been shown (Kröse and Julesz, 1989) that an invalid cue presented prior to the stimulus may affect performance. Even distracters at a higher eccentricity than the target affect performance if these distracters are presented 40 ms before stimulus onset (Gathercole and Broadbent, 1987). By analogy to distracters that are presented before stimulus onset, it is possible that distracters presented *foveally* may affect the orienting of attention. They are responded to somewhat more rapidly, as shown in Appendix B.

We have shown that even in a nonsearch task, additional background elements can affect discrimination RTs and the magnitude of the effect depends on the positions of these background elements relative to the target and, for some observers, relative to the fovea. When the effect of changing the number of background elements in a search task is used as an argument for serial processing, special attention has to be given to the positions of the target and background elements to distinguish spatial interactions of the type observed here from serial processing.

Acknowledgements

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Appendix A: Effect of Training

During the experiments, a substantial learning effect was found. For this reason, all observers went through a training period in which practice trials of the no-distractor condition were done. The observers were shown their average RT and number of errors after every 110 trial session. Data on performance during this period were recorded for three observers. These data are plotted in Figure A-1 as the average RT for each day of testing. Data for the no-distractor condition obtained during the main experiments are also shown. Observer A started with the main experiments on Day 3 and had 11 practice runs (of 110 trials each). Observer C started on Day 3 after 17 practice runs, and Observer E started on Day 4 after 15 practice runs.

----insert Figure A1----

Figure A-1 also shown the magnitude of the day-to-day variations in RT. In this paper we expressed performance as the difference between the RT *with* distracter(s) and the RT *without* distracter to factor out some of this variability.

Appendix B: Effect of Eccentricity

For eccentricities less than 20°, performance on a variety of visual threshold tasks varies approximately linearly with eccentricity (Weymouth, 1958; Anstis, 1974) when this performance is measured with visual acuity. How does performance depend on eccentricity if the task is above threshold, and RT's are measured? An increase in RT with increasing eccentricity was found by

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Lefton and Haber (1974), using a same/different task with small characters on the horizontal axis. In our experiment the task was identification (not a same/different discrimination) and our elements were twice the size of those used by Lefton and Haber, so we decided to study the effect of eccentricity on RT ourselves, using both the horizontal and tne vertical axes.


-----insert Figure A2-----

The results for two observers are given in Figure A-2. Both observers show an increase in RT with increasing eccentricity. For Observer F, this increase begins at small eccentricities and continues almost linearly whereas for Observer D, the RT's a.e essentially independent of eccentricity at small eccentricities, but increase sharply beyond about 4° eccentricity. For small eccentricities, we found no significant effect of radial anisotropy: the vertical and horizontal RT's were the same. In these experiments, RT for the most eccentric location in the upper visual field (6° vertical) was elevated because of its nearness to the edge of the display. This problem was avoided in the experiments reported in the body of this report by placing the fixation cross below the center of the display. For the most eccentric horizontal target positions, there was a difference between the left and the right (of the observer): target presentation to the right of the fixation point resulted in a lower RT than target presentation to the left of the fixation point. This agrees with the data of Perry et al. (1984) on the distribution of ganglion cell density across the retina: at a given retinal eccentricity, ganglion cell densities are several times greater along the nasal horizontal meridian than along the other three meridians.

Figure Captions

Figure 1   Positions of distracter used in single-distracter experiments. In this example, the

distracter is presented at Position 1. The target (∩ in this illustration) was always in

the same location. The small cross, which was not visible during the trials, is the

fixation point.

Figure 2   Change in RT caused by the presence of a single distracter (which could be a ∪ or a

∩). Data are shown for three observers and a range of target-distracter spacings.

Distracter positions refer to the naming scheme shown in Fig. 1.

Figure 3   a) Schematic diagram of position of distracter relative to target. The distracter was

presented at a constant distance of 3.1° from the target at various angles. At -90°

orientation, the distracter was on the observer's fovea. b) Change in RT caused by the

presence of the distracter, as a function of distracter position. Data are shown for four

observers.

Figure 4   The target element (∩ in this example) surrounded by either one or two rings of

distracters (∩'s and ∪'s). The small cross shows where the subject fixated (the cross

was not present during the trials). Fixation accuracy was ensured by image

stabilization.

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Figure 5   Change in RT caused by the addition of one or two rings of distracters. Also shown

for comparison is the maximum ΔRT obtained for each observer and each spacing in

the single-distracter condition. See Fig. 2.
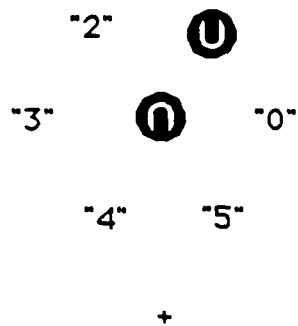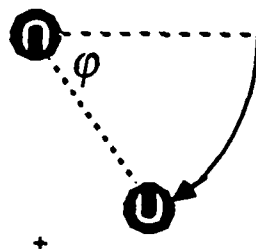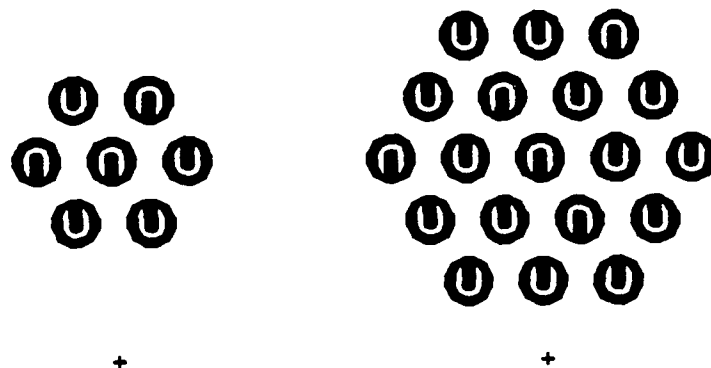
"2"   🔵

"3"   🔵   "0"

"4"   "5"

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"Spatial Interactions in Rapid Pattern Discrimination"
Fig. 1
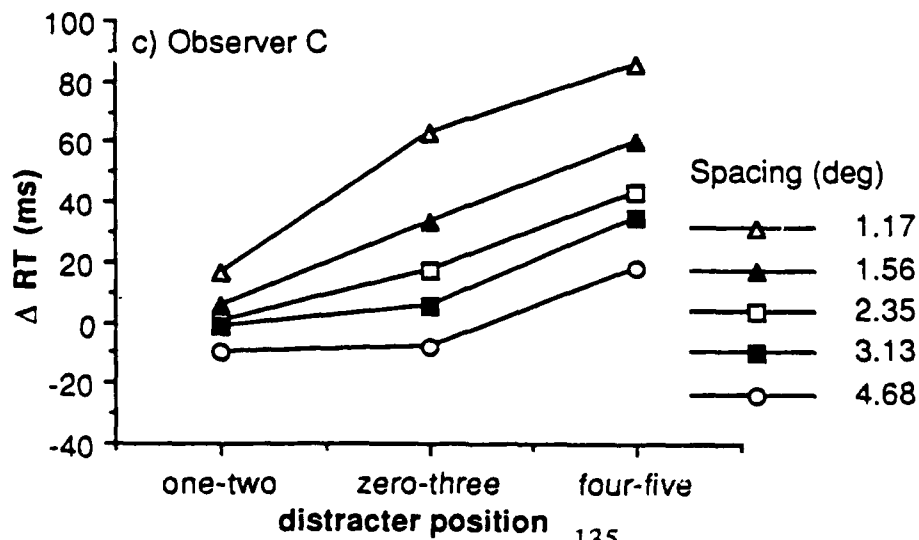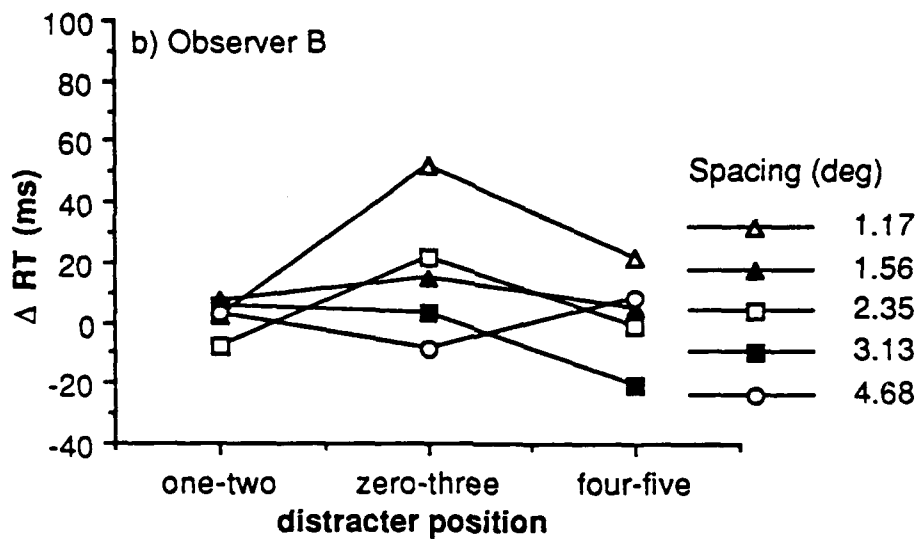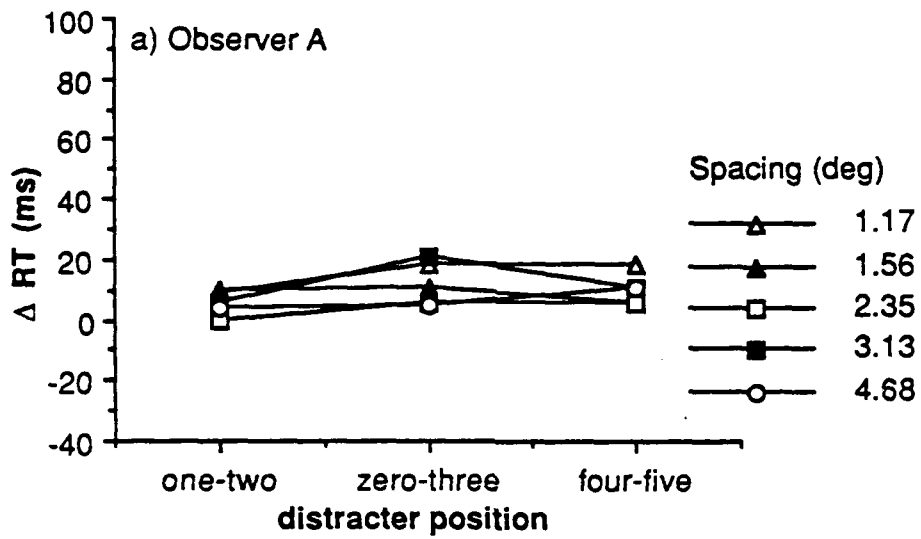
Ben J.A Kröse and Christina A. Burbeck
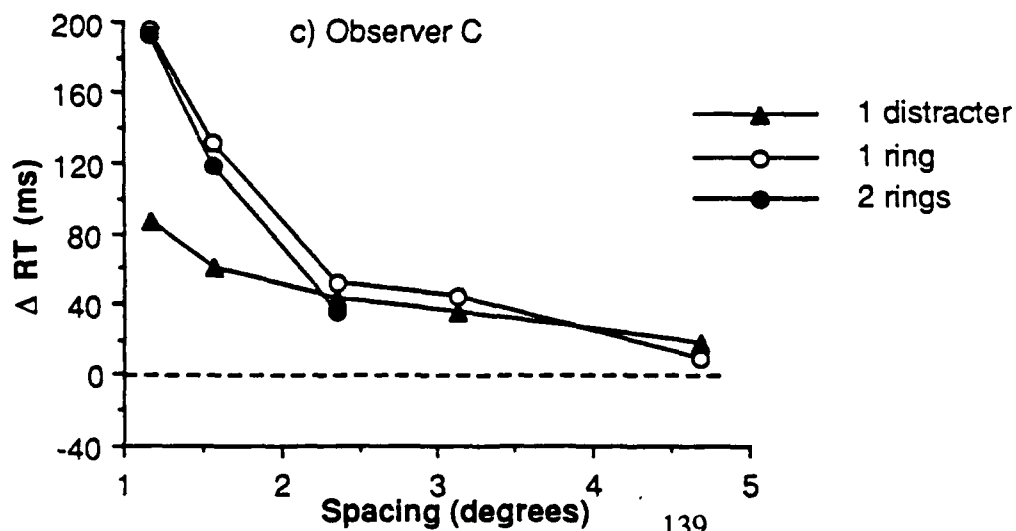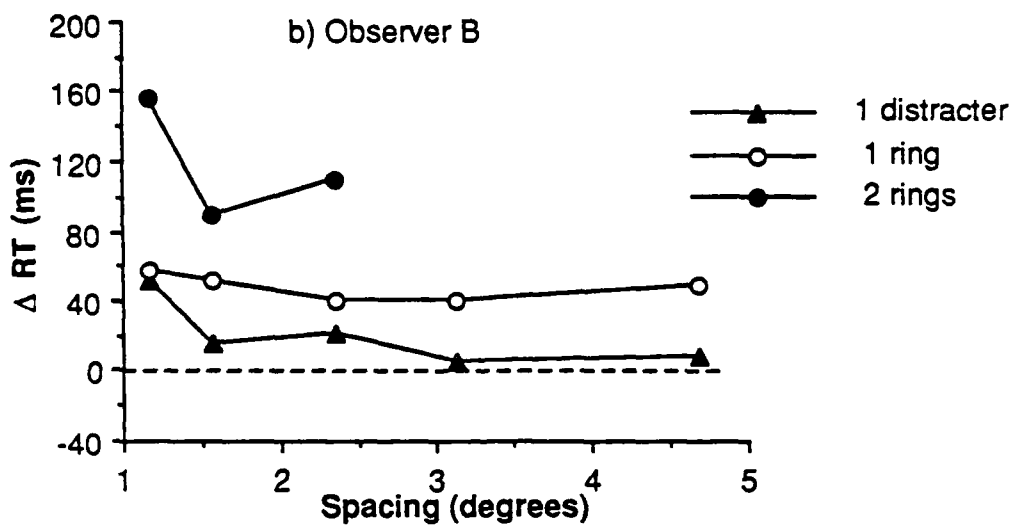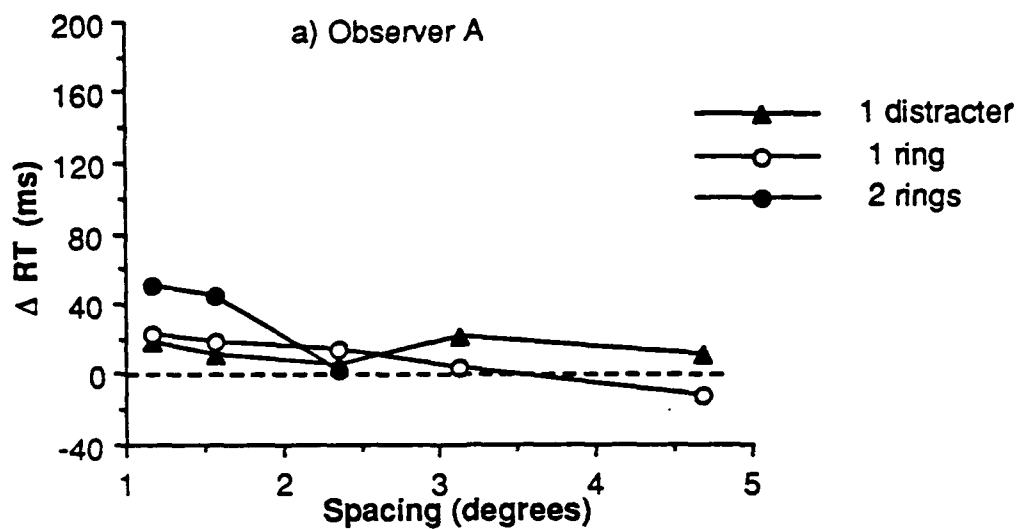"Spatial Interactions in Rapid Pattern Discrimination"
Fig. 2
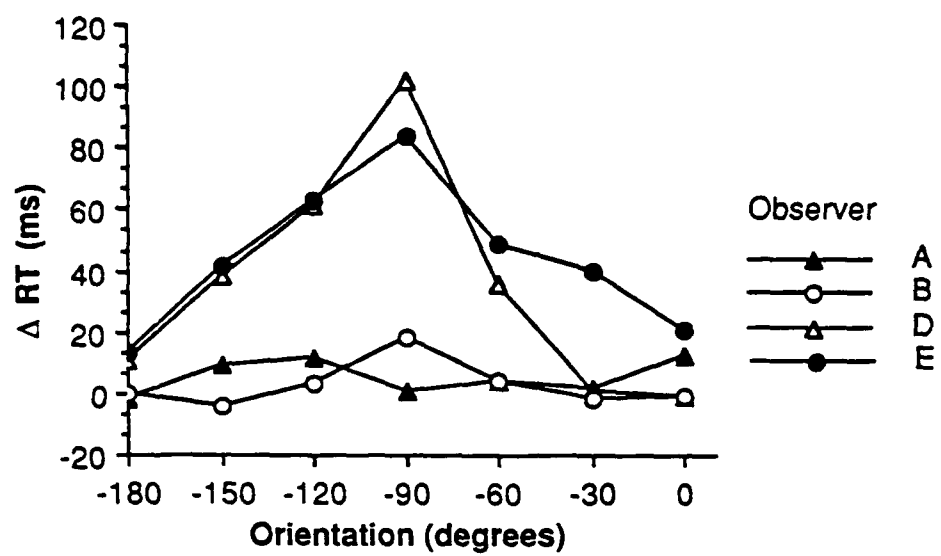
Ben J.A Kröse and Christina A. Burbeck
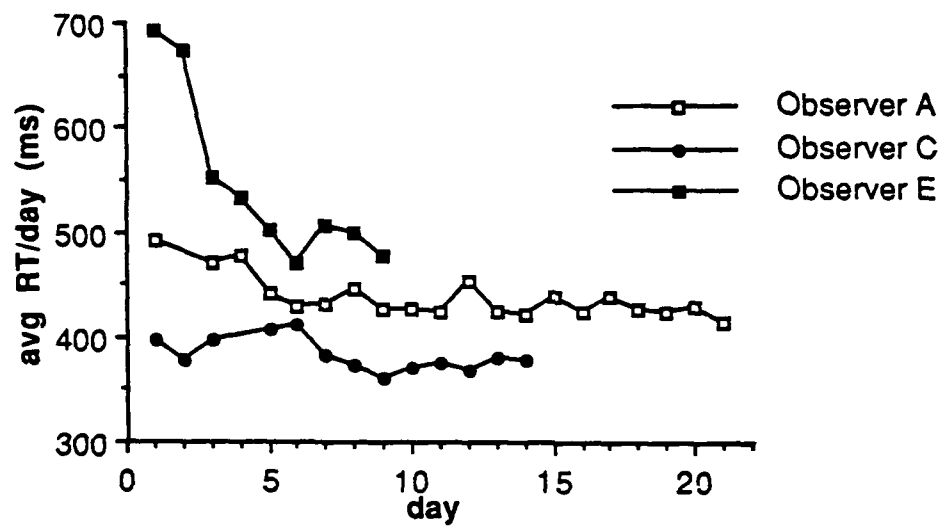"Spatial Interactions in Rapid Pattern Discrimination"
Fig. 3

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"Spatial Interactions in Rapid Pattern Discrimination"
Inset for Fig. 3

Ben J.A Kröse and Christina A. Burbeck
"Spatial Interactions in Rapid Pattern Discrimination"
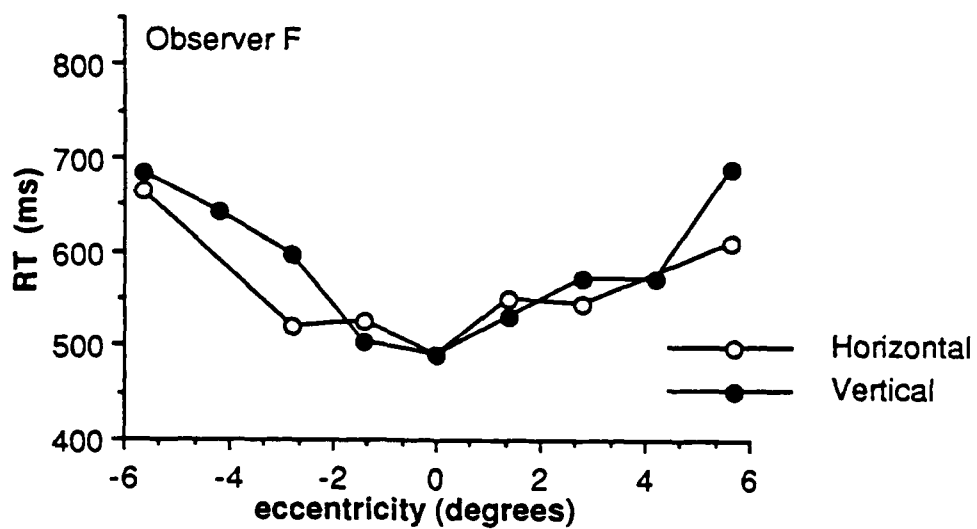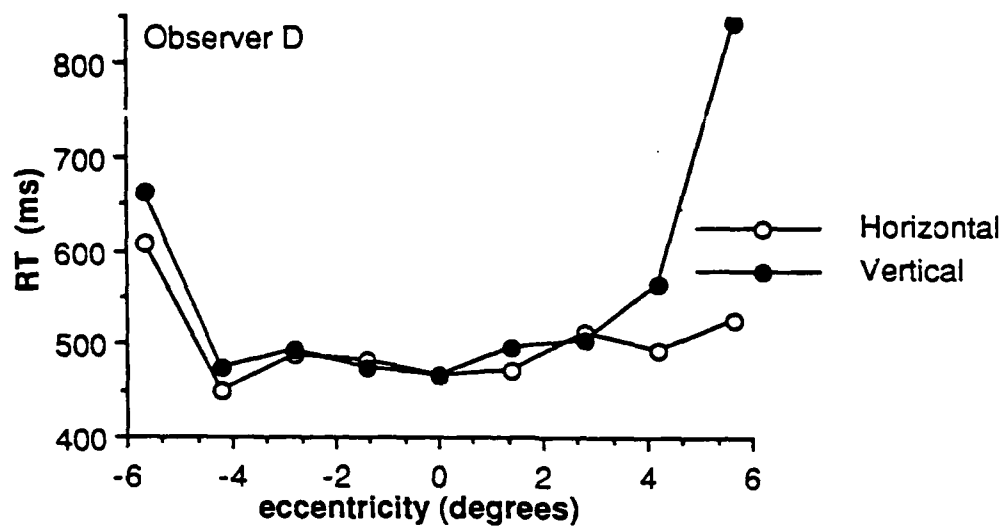Fig. 4

a) Observer A

b) Observer B

c) Observer C

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Fig. 5

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Fig. A-1

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Ben J.A Kröse and Christina A. Burbeck
"Spatial Interactions in Rapid Pattern Discrimination"
Fig. A-2

Appendix E

THE LENGTH EFFECT IN SEPARATION DISCRIMINATION

Yen Lee Yap

In preparation for *Vision Research*

THE LENGTH EFFECT IN SEPARATION DISCRIMINATION *

Yen Lee Yap

INTRODUCTION

The influence of length in localization thresholds was first speculated upon in 1899 by Herring, who postulated that vernier thresholds, which were smaller than separation between cones, could be achieved by averaging the local sign of the retinal receptors excited by the image of the stimulus. This early idea of the effect of length fell into disfavor after Westheimer and McKee (1977) demonstrated that increasing stimulus length in the fovea does little to improve the better-than-resolution (hyperacuity) thresholds for separations of a few arc min in vernier alignment and separation discrimination. In contrast to this finding, Andrews and Miller (1978) showed that length has an effect on bisection judgements for a larger target-to-target separation (82' arc min), improving the thresholds as the length of the targets was increased. Likewise, Levi, Klein and Yap (1987) also found a significant improvement in bisection and separation-discrimination thresholds from adding independent samples along the length of the stimulus. The improvement is stronger in the periphery than in the fovea, implying that the eccentricity of the targets is an important factor in the length-effect. However, recent data from Burbeck and Yap (in press–a) indicated that the length effect in separation discrimination results not from the retinal eccentricity of the targets per se, but instead from the interaction of both the separation and the eccentricity. The effect of length on separation-discrimination thresholds for a given separation was stronger in the periphery than in the fovea and for targets presented at the same eccentricity, it was stronger for a small than a large separation.

This result poses difficulties for models of localization which rely solely on the output of local spatial filters (Wilson and Gelb, 1984; Carlson and Klopfenstein, 1985; and Klein and Levi, 1985). Such simple channel models would predict that the strength of the length effect would increase for increasing separation if the width of receptive field of a local spatial filter were assumed to be roughly proportional to its length, e.g. as for V1 cells of the macaque and rhesus monkeys (Hubel and Wiesel, 1974; Dow, Synder, Vautin and Bauer, 1981; and Van Essen, Newsome and Maunsell, 1984). Furthermore, the response of size- or frequency-tuned mechanisms by itself cannot easily explain why

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manipulating the spatial frequency content of the stimulus produces little change in separation-discrimination thresholds (Morgan and Ward, 1985 and Toet and Koenderink, 1988) except for short exposure durations (Burbeck, 1986 and Burbeck and Yap, in press-b).

Performance of separation discrimination has been modelled with some success as a two-stage process in which the positions of the individual targets are initially processed by a set of local spatial filters with the relative separation of the targets being subsequently extracted and compared to a referent separation (Watt and Morgan, 1985; Hess, Pointer and Watt, 1989 and Burbeck and Yap, in press-b). The second stage, also known as the separation discriminator, shows a relative insensitivity to the spatial frequency content (Morgan and Ward, 1985; Burbeck,1987;1988; Toet and Koenderink, 1988 and Burbeck and Yap, in press-b) and eccentricity (Yap, Levi and Klein, 1989, Levi and Klein, in press and Burbeck and Yap, in press-a) of the individual targets. On the other hand, the sensitivity of local spatial filters is strongly determined by the spatial frequency content (e.g. Robson, 1966) and eccentricity (Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978; Rovamo, Virsu and Nasanen, 1978). Thus the interaction of separation and eccentricity in the length effect provides an opportunity to investigate the relationship of the local spatial filters to the separation discriminator and to further characterize the separation discriminator.

In the research reported here, we examine the spatial properties of the mechanisms underlying the length effect in separation discrimination by investigating its dependence on the spatial frequency content, eccentricity, contrast and duration of the stimulus.

SEPARATION-ECCENTRICITY INTERACTION AND THE LENGTH-EFFECT

To determine whether the interaction between separation and eccentricity is a general phenomenon which occurs in foveal vision as well as in the peripheral retina, separation-discrimination thresholds were measured as a function of stimulus length for small and large separations in the fovea and at 10° target eccentricity.

Methods

Separation-discrimination thresholds were measured using horizontal lines with a separation of 8 arc min (') in the fovea and with a separation of 1° at 0.5° eccentricity (fovea-centered) and at 10° eccentricity. Viewing was monocular at a distance of 10.3 m for the foveal stimuli and 2.1 m for the 1° separation at 10° eccentricity. The stimuli were presented at 90% contrast $((L_{max}-L_{min})/L_{min})$ on a background of 90 cd/m^2 (Conrac 2400, 19 in diagonal, 60 Hz non-interlaced frames rate, 515 by 512 pixels) for a duration of 150 ms. For the fovea-centered 8' separation and the 1° separation a line-height of 1' was used. A 4' line-height was also used for the fovea-centered 1° separation as well as at 10° eccentricity.

DRAFT

Fig. 1 shows a schematic illustration of the spatial and temporal configurations of the stimuli. For the foveal stimuli, the increase in line length was symmetrical about the midpoint of each line whereas for the peripheral stimuli, line length was increased only in the direction away from the fovea. No fixation mark was used for the foveal stimuli; the observer simply fixated the center of the screen. A fixation spot was used for the peripheral targets. The reported eccentricity of the targets corresponded to the angle between the fovea and the midpoint of the closest vertical edge of each target. To prevent the observer from using the vertical distance of stimulus to the screen edges as a cue, the stimuli were displaced from trial to trial by ±6' for the 8' separation and ±9' for the 1° separation at both eccentricities.

The task of the observer was to decide whether the separation presented on each trial was larger or smaller than the average of the separations presented. Feedback of the correct answer was provided after each trial. Observers learned to do the task quickly and consistently. Each run was preceded by a set of 14 practice trials. The order of runs was non-systematic with respect to length.

Threshold estimates for individual runs were calculated at the 84% correct level by standard probit analysis techniques (Finney, 1971). Geometric means were obtained by combining individual threshold estimates weighted by their inverse variances. Each mean threshold estimate was based on at least 420 trials. The standard errors shown include both within- and between-session variability (Klein and Levi, 1987).

Two observers were used in these experiments. Because data from observer DH had previously been obtained for the 1° separation (4' line height) at both 1° and 10° target-eccentricities, (Burbeck and Yap, submitted), only the 8' separation condition was determined for him. Observer TRM was measured on the all but the 8' separation condition. Both observers had normal or correctable-to-normal vision.

Results

Fig.2 shows that there is an interaction between separation and eccentricity in the length effect both at the fovea and in the periphery. The data for observers DH and TRM of this experiment are shown together for comparison with the replotted data of observers DH and JB from Burbeck and Yap (in press–a). Separation-discrimination thresholds for the fovea-centered stimuli improved more for the smaller separation (8'), than for the larger separation (1°). Although a shorter line height (1') was used for the 8' separation than for the 1° separation (4'), it is unlikely that the difference between the strength of the length effects was due to the difference in the line-heights: observer TRM showed no difference in the length effect for a separation of 1° at 10° eccentricity when the height of the target-lines was changed from 1' to 4'.

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DRAFT

Although the dependence of the length effect on separation and eccentricity cannot readily be explained by a local-spatial-filter model, it is useful to try to account for some of data using the properties of these filters. As the stimulus separation increases, smaller and less sensitive filters appear to be replaced by larger and more sensitive filters to optimize signal strength Burbeck (1986). A two-stage model model can account for the data if the spatial extent of the separation discriminator at the fovea is large enough to sample .nore than one receptive field of the local spatial filters used for the 8' separation and if the spatial extent of the separation discriminator at 10° eccentricity is large enough to sample more than one spatial filter for the 1° separation. This model is also compatible with the finding that for the 1° separation, the effect of length was greater at 10° eccentricity than at the fovea. Because the peak of the contrast sensitivity function shifts to lower spatial frequencies with increasing eccentricity (Koenderink et al., 1978 and Rovamo et al, 1978), the 1° separation may be detected by less sensitive filters at 10° target eccentricity than at the fovea.

THE ROLE OF CONTRAST IN THE LENGTH EFFECT

If the length effect results from contrast integration within the underlying local spatial filters then we should be able to improve thresholds in the same way by making the lines taller instead of longer. To test this prediction, I measured the dependence of separation discrimination thresholds on height.

Methods

Separation discrimination thresholds were measured as a function of line height for a 1° separation at 10° eccentricity. A line length of 4' was used for both observers JB and DH and in addition, a line length of 30' was also used for observer JB. The center-to-center separation was kept constant as line height was increased. All other details were similar to those of the previous experiment.

Results

Fig.3 shows thresholds plotted as a function of increasing height (crosses) and for comparison, the data from Fig.2 in which the length was increased. For the tall lines with a 4' length, both observers showed a very similar improvement in the separation-discrimination thresholds with increasing line height up to 15 or 20' compared to the decrease obtained with increasing line length with a 4' height. Observer DH showed slightly better thresholds for increasing height compared to increasing length. It is likely that this small difference is due to practice as the threshold versus height function was measured after the threshold versus length function. Thus the length effect for relatively short lengths appears to be caused by an increase in the target contrast. This conclusion is supported by the finding that for high-contrast targets, additional height samples do not improve

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separation-discrimination thresholds whereas additional length samples do (Levi et al., 1987).

Fig.4 shows separation discrimination thresholds of observer JB plotted as a function of area for line lengths of 4' and 30' and a line height of 4'. In comparison to the 4' long lines, which improve in the same way with increasing area as the 4' high lines, the thresholds for the 30' long lines improve little if any with increasing area i.e. line height. Thus the residual length effect at longer lengths cannot not be attributed to contrast integration. Instead the data suggest that the threshold decrease is caused by the presence of additional samples of the separation. This result is in keeping with the findings of Levi et al. who used high-contrast targets.

ISOLATING THE LENGTH EFFECT FROM CONTRAST EFFECTS

To isolate the length effect from the influence of contrast, the stimulus strength was increased by making the lines taller and/or the background dimmer. for independent confirmation, line targets with a constant effective contrast were also used. Separation discrimination thresholds were measured as a function of length for separations of 8' at the fovea, 1° or 5° at 10° eccentricity.

Methods

For the separation of 1° at 10° eccentricity, the length effect was determined for a height of 15' with a dim versus normal background. The dim background increased the ratio of target luminance from 90% of the background to many times that of the background. In addition, the length effect was also determined for a height of 4' with a dim background. For the separation of 5° at 10° eccentricity, the length effect was determined for a height of 15' with a normal background. A viewing distance of 1 m and a vertical trial-to-trial stimulus displacement of ±19' was used for the 5° separation as in Burbeck and Yap (submitted–a).

Contrast detection thresholds were measured for observer TRM using a constant-stimuli 2-alternative forced-choice paradigm for the separation of 1° at 10° eccentricity using 15' tall lines on a normal background. The task of the observer was to report whether the target appeared in the upper or lower field. To avoid confusion in identifying the upper and lower positions of the target, the vertical and horizontal coordinates of the targets were kept unchanged from trial to trial. All other experimental details were the same.

Results

Fig.5 shows the changes in the length effect for the 1° separation at 10° eccentricity as the stimulus strength was increased by increasing the target height and in addition, the target contrast for observers DH and TRM. Also shown are the data for the original 4'

height condition on a normal background. Increasing the stimulus strength by increasing the area to 15' improved thresholds most for the shortest lengths and less as the lengths increase. Making the lines taller and dimming the background at the same time resulted in a further improvement at all lengths. The stronger influence of contrast for short line targets compared to the weaker influence for long line targets is compatible with our earlier results (Figs.3 and 4) and the idea that the line targets for this condition are being detected by spatial filters with relatively small and insensitive receptive fields. The residual length effect showed a shallow slope but extended well beyond the 8-12' extent of the area showing strong contrast integration. This is in agreement with our earlier result (Fig.4) and suggests that additional separation-samples are being used by the mechanism/s of the second stage.

Fig.6 shows the contrast-detection thresholds for the 1° separation at 10° eccentricity using 15' tall lines for observer TRM. Unlike the separation-discrimintation thresholds, the contrast-detection thresholds improve steeply and linearly with increasing line length up to a length of 100'.

Fig.7 shows the threshold versus length function for separation discrimination using the 15' tall line targets set to a contrast 1.5 times the detection threshold at each line length for observer TRM. Also shown for comparison is the threshold versus length function for line targets of the same height on a dim background (for high contrast). The function for the constant-effective-contrast targets closely paralleled the function for dim background, verifying that the use of the 15' tall lines together with the dim background succeeded in isolating the length effect from the effect of contrast. Thresholds for the dim background condition were 0.2 to 0.3 log units lower on average than the thresholds for the 1.5 times-detection-threshold condition, supporting previous reports that contrast plays a small role in separation discrimination for targets with a contrast 2-3 times above the contrast detection threshold (Burbeck, 1986 and Morgan and Regan, 1987).

Fig.8 shows that for the 5° separation at 10° eccentricity increasing the stimulus height to 15' and 32' improved thresholds mainly for lengths shorter than 4-10', resulting in a very shallow length effect for observers JB and DH respectively. The smaller effect of contrast for the 5° separation compared to the 1° separation at the same eccentricity is in agreement with the hypothesis that the local spatial filters detecting the larger stimulus are more sensitive than the filters detecting the smaller stimulus. A second finding of interest is that the length effect for the larger separation was reduced compared to the smaller separation. This implies that for the 5° separation, the receptive fields of the underlying spatial filters are sparser relative to the extent of the separation discriminator/s than for the 1° separation. Both these findings are compatible with the notion that local spatial filters with larger, more sensitive and more sparsely-spaced receptive fields are used to detect the targets for the 5° separation than the 1° separation.

ARE LONG LINE TARGETS SAMPLED BY ONE
OR MORE SEPARATION DISCRIMINATORS?

Our results up to this point indicate that the length effect consists of a small region within which the influence of contrast predominates and a larger region within which additional separation samples appear to be integrated. Does this larger region reflect the activity of one or more separation discriminators? Using a bisection task, Burbeck and Yap (submitted–b) showed that the comparison of one separation to another is done sequentially. If more than one bit of separation information is extracted from long line targets, then the length effect should extend to longer lengths for long exposure durations than for short exposure durations.

Methods

The threshold versus length function was determined using a long exposure duration of 500 ms for the 8' separation at the fovea for observer DH. Since the use of a longer exposure duration also increases in the stimulus strength for high spatial frequencies, for comparison, the function was also determined for an increase in the stimulus strength by dimming the background. All other experimental details were kept the same.

Results

Fig.9 shows that increasing the stimulus duration and/or dimming the background produces an improvement on the length effect for the 8' separation at the fovea for observer DH. Also shown for comparison are the data for the 1' height with normal background. While the dim background lowers threshold mainly on the short lengths, for the long lengths, the longer duration of 500 ms continues to lower the threshold for the long lengths. This difference between the effect of prolonging exposure duration versus increasing target contrast suggests that the dim background is more effective in stimulating the small-relatively-insensitive receptive fields of the local spatial filters detecting each target but that the longer exposure duration permits more than one separation discriminator to be used. Note that the length effect flattens at 3' for the 150 ms duration but extends at least up to 25-50' for the 500 ms duration. This suggests that for the 8' separation at the fovea, the extent of the separation discriminator is 3'.

SUMMARY AND DISCUSSION

This study shows that performance of separation discrimination was improved by extending the length of the individual targets. The length effect was shown to depend on both separation and eccentricity both in the fovea and in the periphery. For short lines, the improvement was mainly due to contrast integration while for long lines, it was due to the availability of additional bits of separation information. These additional bits of information appeared to be processed by multiple separation discriminators. These

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results are difficult to account for solely in terms of the output of local spatial filters but they support the hypothesis that at least one additional stage of processing is required to account for performance of separation discrimination. Furthermore, these results indicate that in the absence of other interfering stimuli, smaller, less sensitive and more densely-spaced spatial filters are used to detect the individual targets for small separations compared to large separations at the same eccentricity.

Fig.10 shows that the residual length effect is more pronounced for the 1° separation in the periphery than in the fovea for observer DH. Also shown for comparison are the residual length effects for the 8' separation and the 5° separation on the same observer. Levi et al. (1987) also report that the dependence of bisection thresholds on length samples in the fovea was shallower compared to the dependence at 2.5° eccentricity. Levi et al. attribute this difference to the cortical oversampling of each stimulus sample at the fovea relative to the undersampling in the periphery. In this case however, the weaker foveal length effect cannot merely be due to cortical oversampling of the stimulus relative to the periphery since the length effect for a different separation (8') in the fovea is stronger. It seems likely that the separation of 1° was detected by local spatial filters of the same size in both the fovea and at 10° eccentricity. Also, the receptive fields of the local spatial filters detecting this stimulus at the fovea are probably more sensitive and as least as densely-packed as at 10° eccentricity. Since it is unlikely that separation discriminators are more dense in the periphery than in the fovea, this difference between the strength of the length effect for a fovea-centered 1° separation and a 1° separation at 10° eccentricity may be due to a difference between the type of mechanisms involved at the second stage.

Recent studies investigating the dependence of separation-discrimination and bisection thresholds on separation and eccentricity (Levi, Klein and Yap, 1988; Levi and Klein, in press and Burbeck and Yap, in press–b) indicate that there may be two types of mechanisms involved in separation discrimination. This hypothesis is based on the finding that thresholds for separations smaller than the eccentricity of the targets are strongly dependent on the separation of the targets and weakly dependent on the target eccentricity whereas thresholds for larger separations are independent of the target separation and strongly dependent on the target eccentricity. The present finding of two different strengths of the length effect lends support to this hypothesis. Furthermore, the residual length effect for the 5° separation at 10° eccentricity is very similar to the residual length effect for the fovea-centered 1° separation but different from the residual length effects for the other two conditions which resemble each other.

The residual length effects in this study are all shallower than the slope of 0.5 found by Levi et al. (1987) for the dependence of bisection thresholds on length samples using high contrast targets at 2.5° eccentricity. Levi et al. found that the distance between effective samples was approximately 2' at 2.5°. It is likely that the slopes of the length effect obtained in this study would be steeper if they were to reflect thresholds dependence on the number of 1' samples rather than the overall length of the line targets.
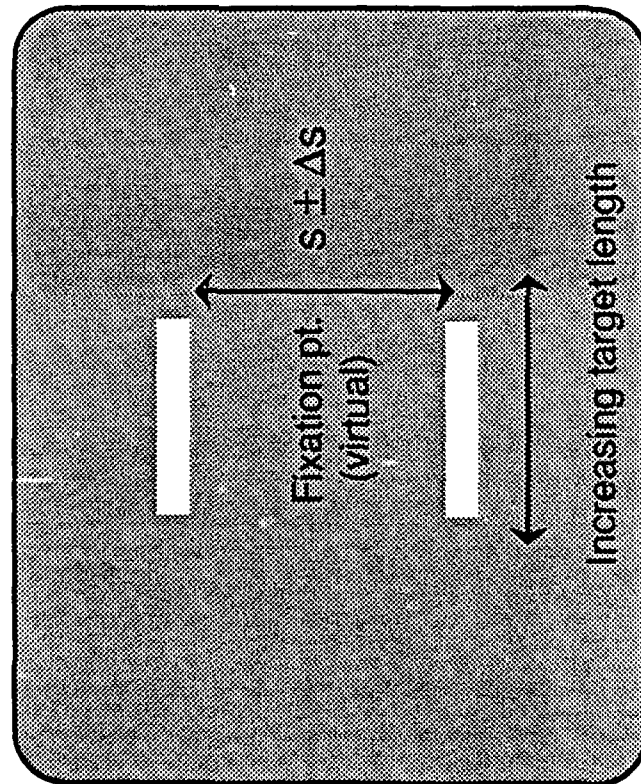
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DRAFT

FIGURE CAPTIONS

Fig.1   Schematic of the fovea-centered and peripheral stimuli used to measure the effect of target length on performance of separation discrimination. The height refers to the vertical extent of each target. The stimuli were presented with an abrupt onset and offset for a duration of 150 ms.

Fig.2   Separation discrimination thresholds plotted as a function of line length for separations of 8' and 1° centered at the fovea and separations of 1° and 10° eccentricity for observers DH (a), TRM (b) and JB (c). For each eccentricity, thresholds improved more steeply with length for the smaller separation than the larger separation. For the separation of 1°, the length effect was stronger for the more peripheral targets.

Fig.3   Separation discrimination thresholds plotted as a function of increasing height (crosses) and for comparison, the data from Fig.2 in which length was increased for observers DH (a) and JB (b). In the former condition the target length was fixed at 4' while in the latter condition the height was fixed at 4'. Thresholds improved with increasing height in the same way as with increasing length up to a height of 15 or 20'.

Fig.4   Separation discrimination thresholds plotted as a function of increasing target area for target lengths of 4' and 30' and a target height of 4' for observer JB. Thresholds for the line length of 30' did not improve significantly with increasing area (line height) unlike the the thresholds for long lines with an equivalent area.

Fig.5   Separation discrimination thresholds plotted as a function of increasing target length for 4' and 14' target heights on a normal background and for 14' target height on a dim background for observers DH (a) and TRM (b). Increasing the target height to 14' improved performance more strongly for the shorter line lengths and less for the longer lines. Dimming the background produced a further improvement at all lengths for observer DH and only for the shorter lengths for observer TRM. The residual effect showed a shallow slope but extended well beyond the 8' to 12' extent of the area showing strong contrast integration.

Fig.6   Contrast detection thresholds plotted as a function of line length for the 1° separation at 10° eccentricity with a 14' target height for observer TRM. The contrast discrimination thresholds improve steeply and linearly with increasing length up to 100' line length.

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Fig.7   Separation discrimination thresholds plotted as a function of increasing target length for the 1° separation at 10° eccentricity using a 14' target height with a target contrast of 1.5 times the detection threshold or on a dim background for observer TRM. The two functions parallelled each other closely verifying that the use of the 14' target height together with the dim background was successful in isolating the length effect from the effect of contrast.

Fig.8   Separation discrimination thresholds plotted as a function of increasing target length for separation of 5° at 10° eccentricity using 4' and 32' target heights for observer DH and 4' and 15' target heights for observer JB. The improvement in performance occurred largely for lengths shorter than 4-10' resulting in a very shallow length effect.

Fig.9   Separation discrimination thresholds plotted as a function of increasing target length for a fovea-centered separation of 8' using a 1' target height and exposure durations of 150 or 500 ms with and without a dim background for observer DH. The dim background was more effective for short lines while the long exposure duration was more effective for long lines.

Fig.10   Separation discrimination thresholds plotted as a function of increasing target length for conditions in which the residual length effect was isolated for observers DH and TRM. For the 8' separation, the 1'-tall targets were presented on a dim background for 500 ms (replotted from Fig.9). For the fovea-centered 1° separation the target height was 4' (replotted from Fig.2). For the 1° separation at 10° eccentricity the target height was 14' and the targets were presented on a dim background (replotted from Fig.5). For the 5° separation the target height was 30' for observer DH and 15' for observer JB (replotted from Fig.8).
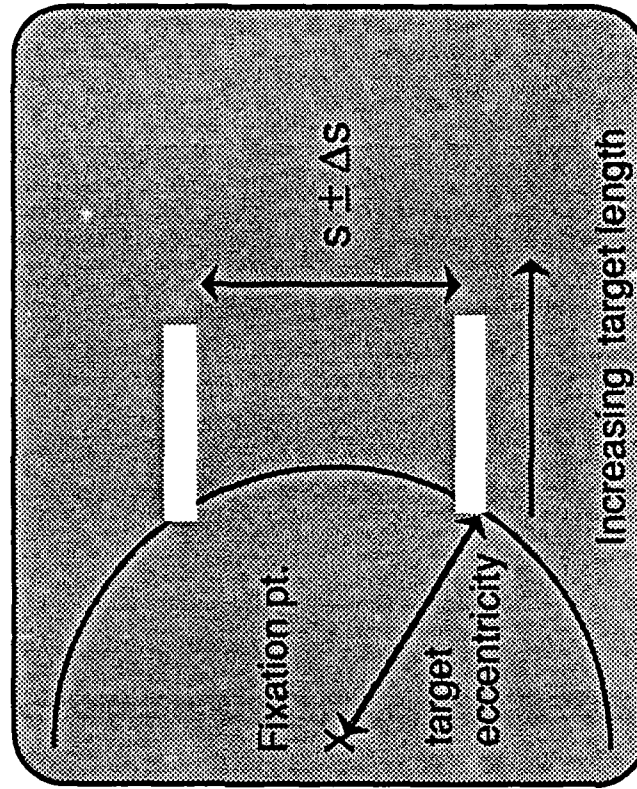
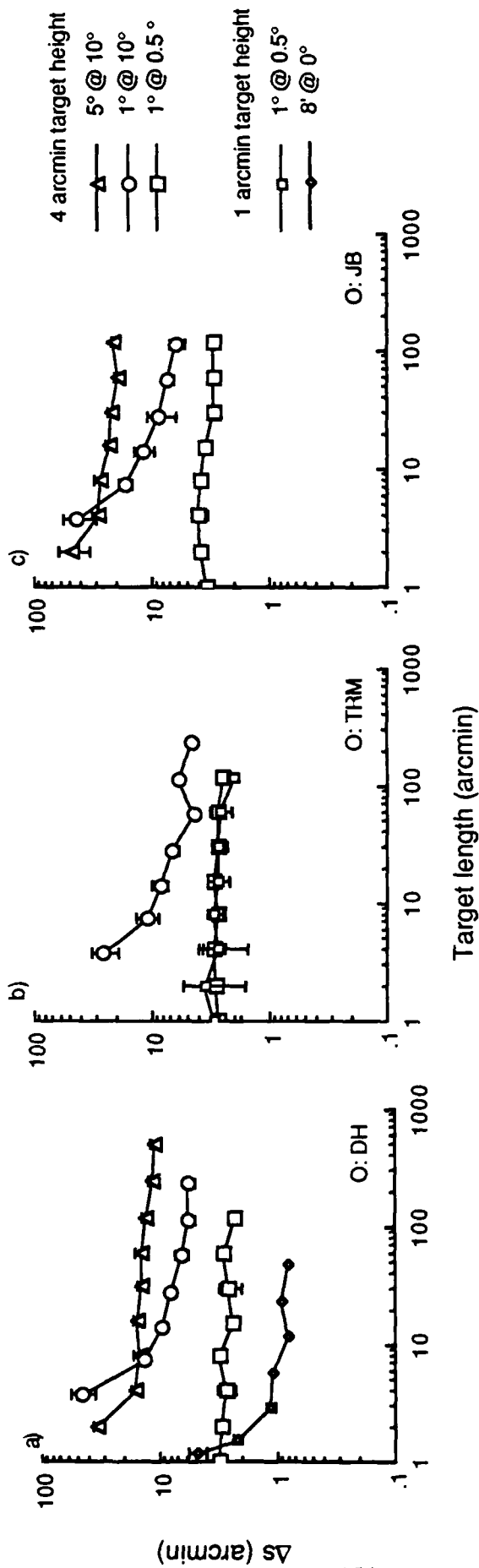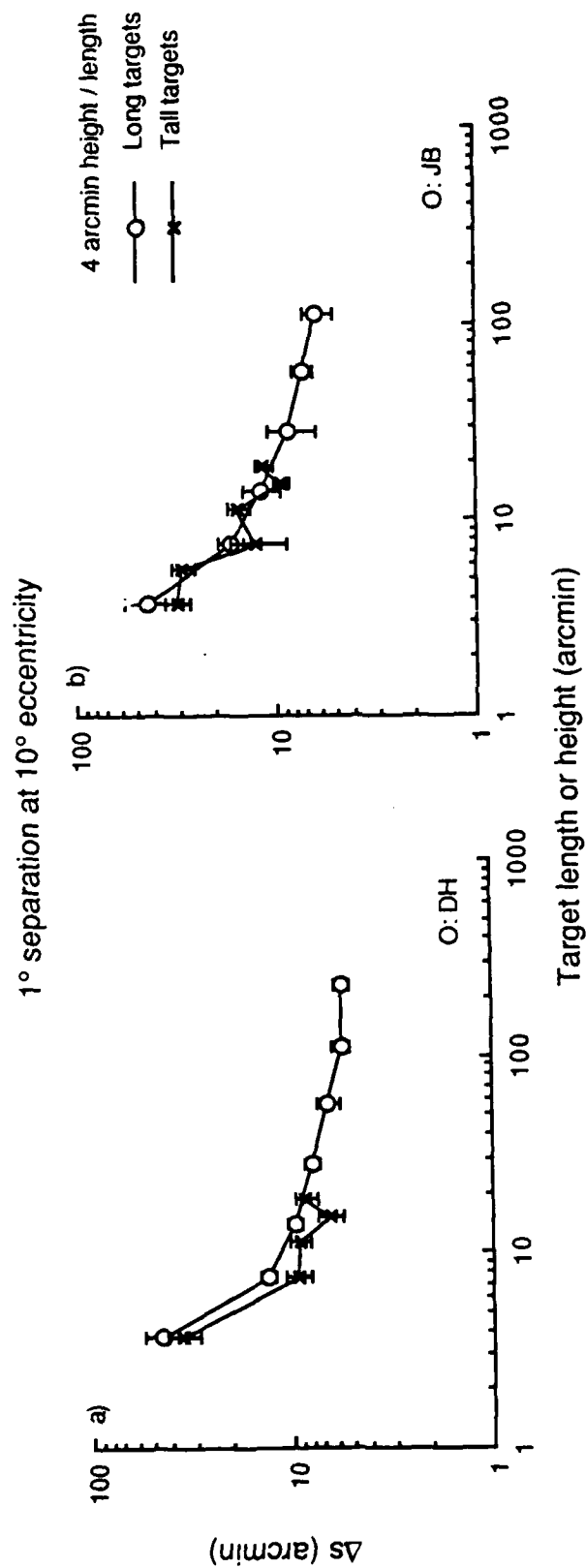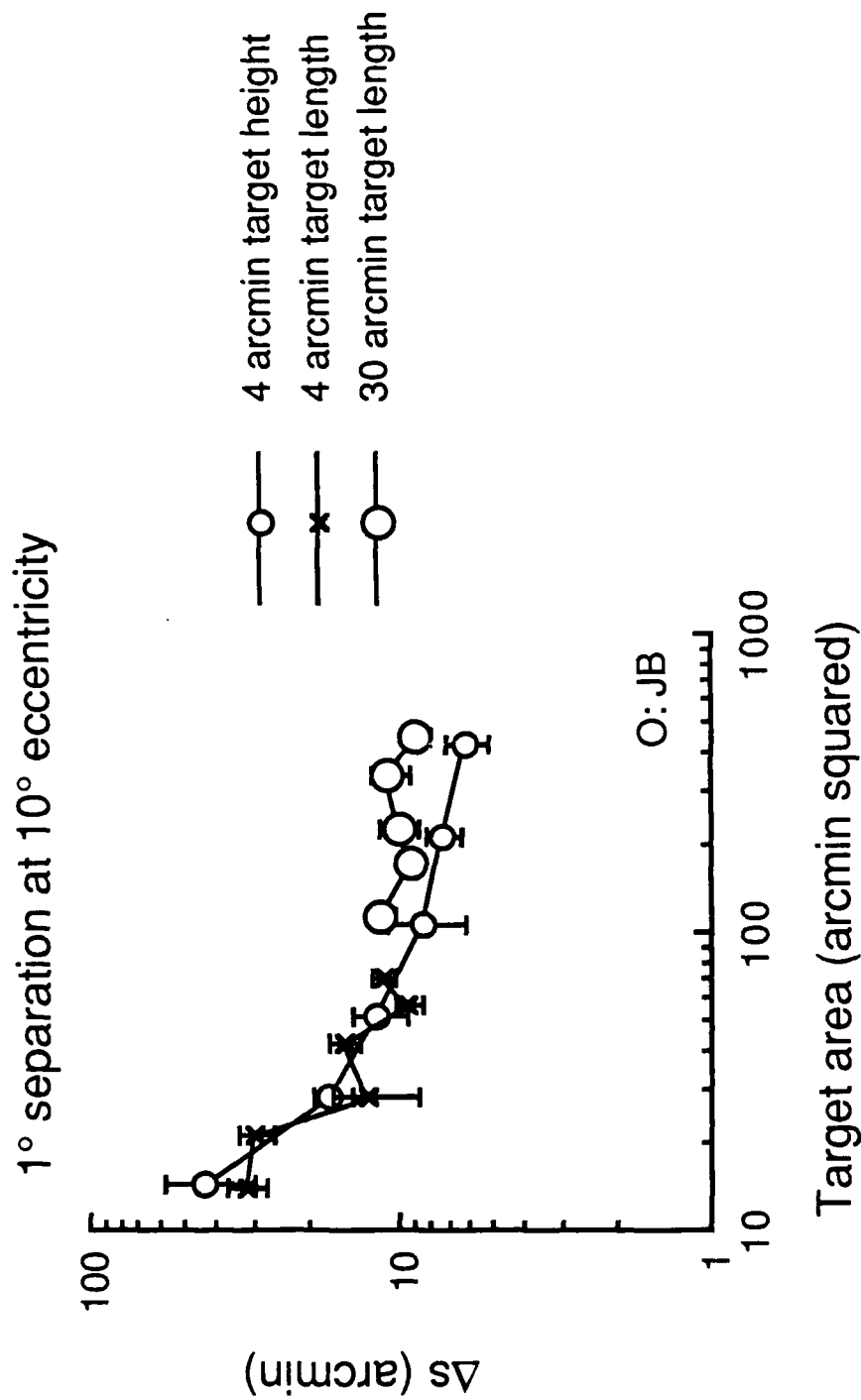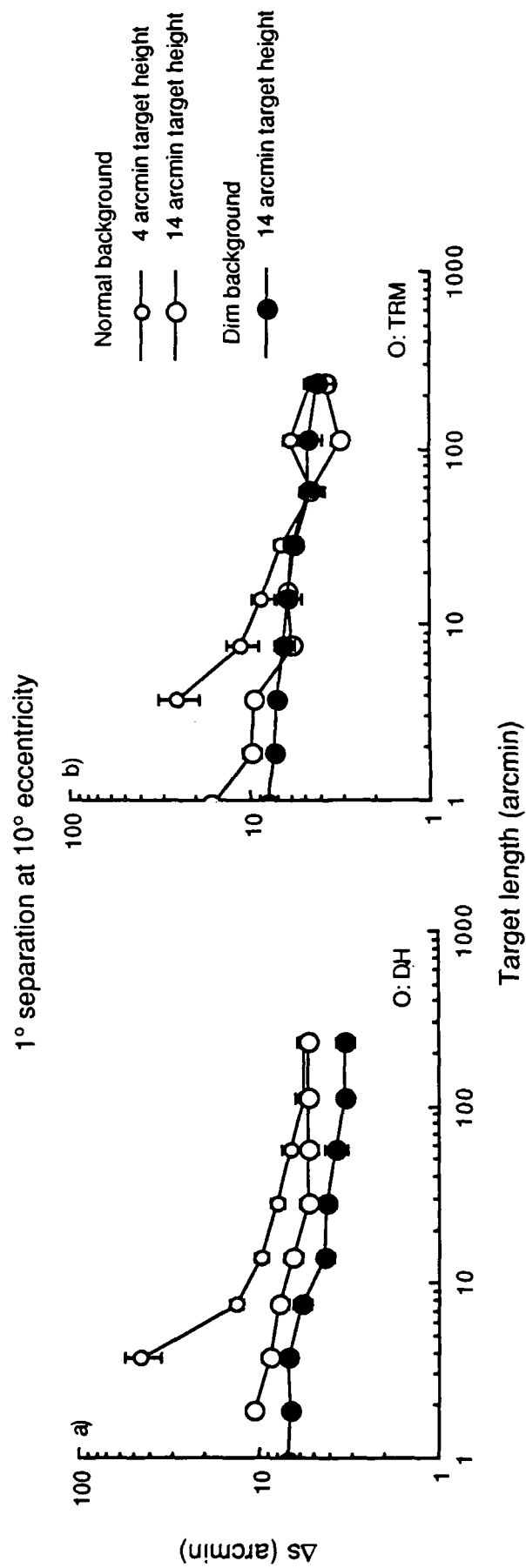Peripheral stimuli

Fovea-centered stimuli

Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 1

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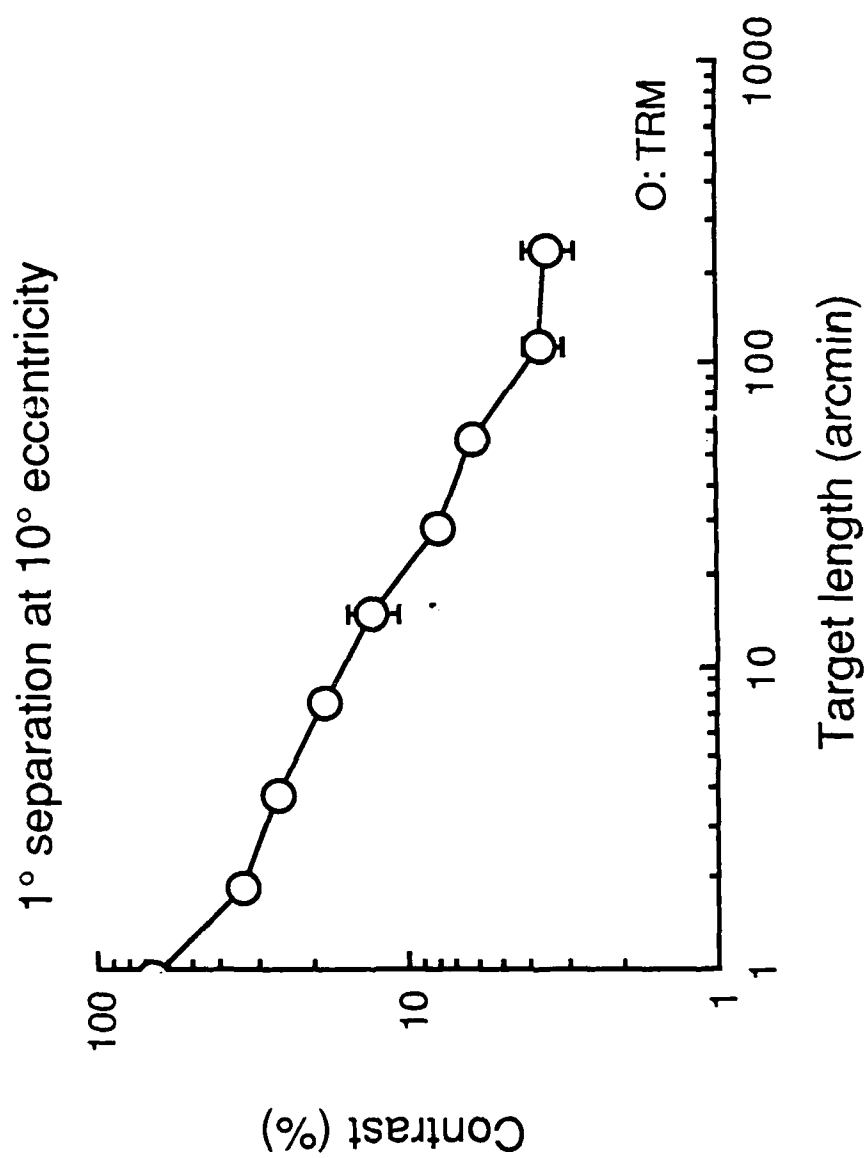Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 2

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1° separation at 10° eccentricity

Target length or height (arcmin)

Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 3

1° separation at 10° eccentricity

Δs (arcmin)

Target area (arcmin squared)

O: JB

- ○ 4 arcmin target height
- ✕ 4 arcmin target length
- ○ 30 arcmin target length

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"Length Effect in Separation Discrimination"
Fig. 4

1° separation at 10° eccentricity

Normal background
— ○ — 4 arcmin target height
— ○ — 14 arcmin target height

Dim background
— ● — 14 arcmin target height

a) O: DH

b) O: TRM

ΔS (arcmin)

Target length (arcmin)

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"Length Effect in Separation Discrimination"
Fig. 5

1° separation at 10° eccentricity

Contrast (%)

Target length (arcmin)

O: TRM

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"Length Effect in Separation Discrimination"
Fig. 6

1° separation at 10° eccentricity

14 arcmin target height
○----- 1.5x detection threshold
● dim background

O: TRM

Target length (arcmin)

Δs (arcmin)

Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 7

1° separation at 10° eccentricity

Target length (arcmin)

Δs (arcmin)

Target height
4 arcmin
15 arcmin
30 arcmin

O: DH

O: JB

Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 8

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8 arcmin separation at 10° eccentricity

normal background
150 ms
500 ms

dim background
150 ms
500 ms

Δs (arcmin)

Target length (arcmin)

O: DH

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Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 9

Residual length effect

Δs (arcmin)

Target length (arcmin)

a) O: DH

b) O: TRM

5° @ 10°
1° @ 10°
1° @ 0.5°
8' @ 0°

Yen Lee Yap
"Length Effect in Separation Discrimination"
Fig. 10

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